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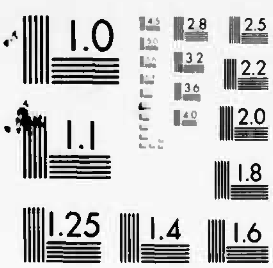

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GRAYS HARBOR AND CHEHALIS RIVER
IMPROVEMENTS TO NAVIGATION
ENVIRONMENTAL STUDIES

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LEVEL II

PRIMARY PRODUCTIVITY AND CARBON INPUT TO GRAYS HARBOR ESTUARY, WASHINGTON

PREPARED BY:

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ENVIRONMENTAL RESOURCES SECTION

US Army Corps of Engineers
Seattle District

SEPTEMBER 1981

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COVER PHOTO: A CAREX MARSH (FOREGROUND) AT BOWERMAN BASIN
IN GRAYS HARBOR.

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The contribution of organic carbon to the Grays Harbor estuary is examined using published information and field studies on marsh plant and benthic algal productivity. This information, in conjunction with a simple mathematical equation, is used to predict the impact of widening and deepening the existing navigation channel on primary production and carbon input to the estuary. Any major impact to carbon input could significantly affect secondary (i.e., herbivore and detrivore) and higher level (e.g., fish) production.

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Twenty three taxa of macroalgae were noted, and these were generally restricted to attachment on hard stable substrata (e.g., logs, roots, boulders). Productivity rates varied among the major algal species. The dense, seasonal green alga Enteromorpha crinita var. clathrata had the greatest rate (1.792 $gC/m^2/hr$), maximum measured rates for the other taxa were: E. intestinalis (1.179 $gC/m^2/hr$), Fucus distichus ssp. edentatus (0.601 $gC/m^2/hr$), macroscopically evident diatom tufts (0.266 $gC/m^2/hr$), Polysiphonia hendryi var. deliquescens (0.166 $gC/m^2/hr$), and Porphyra sanjuanensis (0.090 $gC/m^2/hr$).

Data from the literature and the field studies were used to compute the total amount of carbon contributed to the estuary by aquatic and terrestrial sources. Of the total contribution by all aquatic plant sources (222 x 10^6 kgC/yr), eelgrass contributed the most (125.8 x 10^6 kgC/yr), followed by benthic macro and microalgae (71.3 x 10^6 kgC/yr), marsh phanerogams (16.0 x 10^6 kgC/yr), and phytoplankton (8.9 x 10^6 kgC/yr). Carbon transported to the estuary by rivers was the primary source of carbon (893.1 x 10^6 kgC/yr) to the estuary. The amount of carbon contributed by each source varied with season.

The impact of widening and deepening of the navigation channel on carbon input would be primarily from the removal or burial of areas containing primary producers. Worst case project plans may result in the removal of approximately 3 hectares of benthic primary producers (i.e., marsh plants and algae) in inner Grays Harbor. Disposal of all or most of the dredged material at the mouth of the estuary may decrease the amount of mudflat containing eelgrass and algae in North Bay. These worst case impacts are predicted to cause a 2-percent decline in total aquatic primary productivity (a 0.34-percent decrease in total carbon contribution from all sources). If intertidal/shallow sublittoral regions are not affected, and if most dredged material is disposed of in the open ocean, no major impacts would occur.

PRIMARY PRODUCTIVITY AND ORGANIC CARBON INPUT TO GRAYS HARBOR ESTUARY, WASHINGTON

By

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Seattle, Washington

September 1981

ABSTRACT

The contribution of organic carbon to the Grays Harbor estuary is examined using published information and field studies on marsh plant and benthic algal productivity. This information, in conjunction with a simple mathematical equation, is used to predict the impact of widening and deepening the existing navigation channel on primary production and carbon input to the estuary. Any major impact to carbon input could significantly affect secondary (i.e., herbivore and detrivore) and higher level (e.g., fish) production.

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INTRODUCTION

Background and Objectives. The Seattle District, U.S. Army Corps of Engineers (COE), is studying the impact of constructing and maintaining a wider and deeper navigation channel in Grays Harbor on biological communities of the area. The navigation project will require the initial removal of approximately 22 million cubic yards (c.y.) ($17 \times 10^6 m^3$) of sediment with an annual maintenance removal of approximately 2.7 million c.y. ($2.1 \times 10^6 m^3$) of sediment. Activities related to navigation channel improvements in Grays Harbor may temporarily or permanently affect the productivity (the rate at which plants convert inorganic nutrients to organic matter) of some plant communities (productivity by photosynthetic organisms is referred to as primary productivity) within the Grays Harbor estuary. The food web of the estuary is dependent upon the input of particulate and dissolved organic material from aquatic and terrestrial plant sources. Secondary producers (i.e., small aquatic animals) depend upon this organic material for growth. Organic material, which is rich in carbon, supplies energy needed by these animals and is converted into the structural components of their bodies. The present report generally considers organic matter production and input to the estuary in terms of carbon.

The purpose of this study is to determine the impact of dredging and disposal operations on sources of organic material to Grays Harbor. In order to do this, the following factors must be determined: the sources of organics; the productivity of the plant sources; the amount of material transported from plant sources to the estuary; the temporal changes in the amount of organic material contributed by each source; and the temporal and geographic aspects of the proposed dredging activities.

The objectives of the present study are: (1) review pertinent literature on primary production and organic input for estuaries in the Pacific Northwest and, to a lesser extent, North America; (2) estimate the productivity of certain plant assemblages in Grays Harbor; (3) discuss the impacts of dredging activities on primary production and organic input in Grays Harbor estuary; (4) identify any further information needed to fully evaluate impacts of the project on sources of carbon; and (5) briefly propose the studies that will provide this information.

Approach. To accomplish the above objectives, a review of existing information on estuarine primary productivity is presented. The data provided by this review were coupled with data gathered by a field study of selected benthic plant assemblages in Grays Harbor. The results of field study facilitated a comparison between productivity rates from Grays Harbor to that in other estuaries and provided information on the productivity of benthic plants that was heretofore nonexistent. The rates gathered from the review and the field study were used to derive an estimate of carbon fixation (i.e., primary production) for various regions in the estuary and for the entire estuary. Fluvial sources and oceanic sources of organics were also considered in calculating carbon input.

STUDY AREA

Description. Grays Harbor is a large estuary (1 X $10^8 m^2$ surface area from the mouth to Montesano) located in the southwestern portion of Washington State (figure 1). It is characterized by expansive mudflats, channels, and fringe marshes (figure 2). The Chehalis, Humptulips, Hoquiam, Wishkah, Johns, and Elk rivers all flow into the estuary (figure 2). The Chehalis River and its tributaries contribute the largest volume of water (80 percent of the total volume for all tributary rivers) to the estuary. The portion of the estuary between approximately Moon Island and the city of Cosmopolis is highly developed and industrialized. Several wood processing and log exporting facilities are located along the shoreline in this region. The federally maintained navigation channel extends from Cosmopolis, through the north channel to the convergence with the south channel, and then west to the mouth of the estuary near Westport.

Primary Producers and Other Sources of Carbon to Grays Harbor. Sources of carbon to estuaries include allochthonous material (i.e., carbon from sources outside of the estuary), oceanic input, benthic and planktonic plants, precipitation, and ground water (Teal, 1962; Nixon and Oviatt, 1973; Day et al., 1973; Pomeroy, 1977; Correll, 1978; Naiman and Sibert, 1978; Valiela et al., 1978). Carbon fixation in the estuary is carried out by marsh phanerogams, eelgrass, benthic macroalgae and microalgae, and phytoplankton.

As stated above, marshes in the Grays Harbor are generally restricted to a narrow, fringing band. However, several areas of the estuary (e.g., Oyehut, Bowerman Basin, Westport) contain rather extensive stands of marsh vegetation. Smith et al. (1976) estimated that 16 percent of the area between mean lower low water (MLLW) and extreme high water (EHW) is salt marsh. Mudflats between MLLW and mean higher high water (MHHW) cover approximately 58 percent (5.8 X $10^7 m^2$) of the total surface

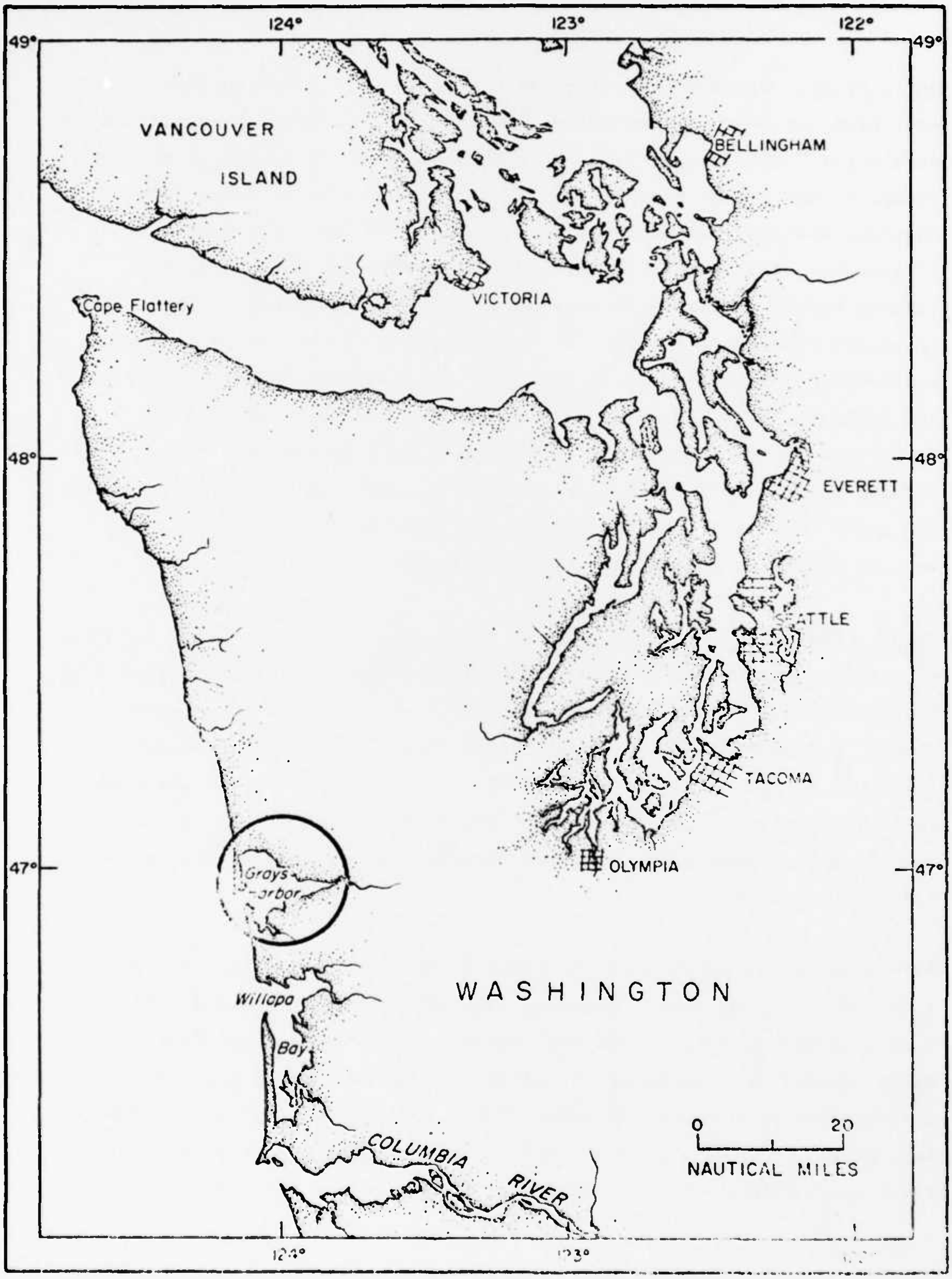

Figure 1. Location of Grays Harbor

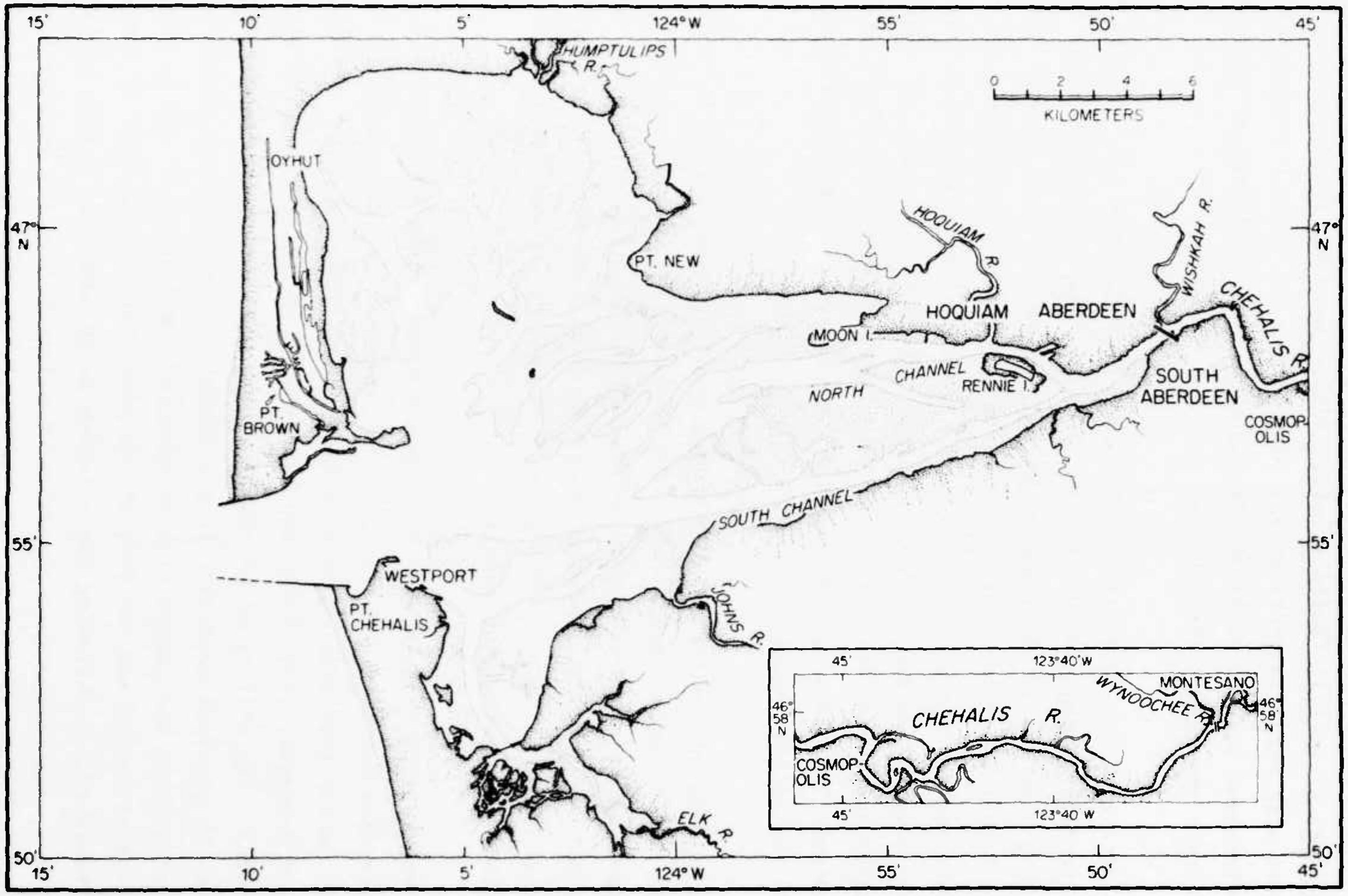

Figure 2. Grays Harbor. Stippled Areas Indicate Mudflats Exposed at MLLW.

area of the estuary (Loehr and Collias, 1981). Much of this area (approximately 5 x $10^7 m^2$) is covered with eelgrass (i.e., Zostera marina, Z. noltii) (Smith et al., 1975). Sediment associated microalgal taxa also occur in these areas. Macroalgae are largely restricted to attachment to hard substrata (e.g., logs, tree roots) which occur in patches throughout the estuary.

Rivers emptying into Grays Harbor flow through forests of Douglas fir (Pseudotsuga menzeisii), western redcedar (Thuja plicata), alder (Alnus rubra), and maple (Acer macrophyllum). Rivers flowing through this type of forest carry particulate, colloidal, and dissolved organic material which may be the primary source of carbon to the aquatic environment of the estuary (Naiman and Sibert, 1978). Intensive logging activities in areas around the tributaries to Grays Harbor increase sediment erosion rates. This fact may result in a significant input of organic material to the estuary above that found in undisturbed areas.

Upwelling in coastal waters affects water characteristics in the outer portion of Grays Harbor (Loehr and Collias, 1981). Cold, nutrient-rich, upwelled water periodically enters the mouth of the estuary and may supply organic and inorganic material to this portion of Grays Harbor. This occurs primarily during low flow periods in the summer when wind direction is from the north.

Recent evidence suggests that organic carbon containing materials produced by the various sources are not equal in their value to the estuarine food webs (Haines, 1976a, 1976b, 1977; Correll, 1978; Haines and Montague, 1979; Estep and Dabrowski, 1980; Hackney and Haines, 1980). The ability of an animal to use organic carbon depends not only on the physical condition (e.g., dissolved, particulate) of the material but also on the composition of material with regard to stable carbon isotope ratios and the time of the year that the material is available. Therefore, in reviewing the relative contribution to carbon presented below, the notion that the value of material from the various sources is not necessary positively correlated with the mass introduced to the estuary must be considered.

LITERATURE REVIEW

Primary Production. Most studies on primary productivity in North American estuaries have been conducted on the East and Gulf coasts. Only a few of the reports listed in bibliographies of coastal marsh investigations are concerned with primary productivity in west coast estuaries (U.S. Fish and Wildlife Service, 1977; Columbia River Estuary Data Development Program, 1980; Morgan, 1980). Data on estuarine primary productivity from the Northeast Pacific are given in reports listed in table 1. The methods listed are reviewed by Linthurst and Reimold (1978) for marsh phanerogams, and for algae by Strickland (1960).

Studies in Grays Harbor include estimates of the productivity of phytoplankton (Westley, 1967; Westley and Tarr, 1965), sediment-associated microalgae (Herrmann, 1971), and marsh plants (Rountree, 1978). Westley (1965) sampled phytoplankton productivity at 14 sites located from the inner to outer portion of Grays Harbor during August and September 1964 and July, August, and September 1965. The productivity rates he recorded ranged from 0.12 to 12.29 $mgC/m^3/hr$ (Westley and Tarr, 1965) and generally were highest at stations located near the mouth of the estuary and lowest in the vicinity of Aberdeen (figure 2). Westley suggested that higher turbidity and possibly increased pollution levels were responsible for lower productivity values in the inner harbor. Herrmann (1971) measured oxygen production and consumption by mudflat organisms during June and August 1966, using bell jars at six sites in the estuary. He found that oxygen production exceeded oxygen consumption and that sediments with a higher organic content had low production to consumption ratios. Net production in sediments ranged from 5.9 to 75.0 $mgC/m^2/hr$ (converted from oxygen production using formulas in Stickland, 1960). Rountree (1978) presents biomass data gathered bimonthly from June 1976 through April 1977 on selected marsh plants in Grays Harbor. He sampled a high marsh site dominated by *Distichlis spicata* and a middle marsh site dominated by

TABLE 1

PREVIOUS STUDIES ON PRIMARY PRODUCTIVITY IN WEST COAST ESTUARIES

(Some of These Authors Do Not Present Productivity Values. However, Their Data Can Be Used to Calculate Productivity.)

Author and Date	Area Studied	Assemblage Studied	Method
Berg, et al., 1975	Nisqually Delta, Washington	Salt marsh phanerogams	Harvest, maximum biomass
Berg, et al., 1980	Nisqually Delta, Washington	Salt marsh phanerogams	Harvest, maximum biomass
Cameron, 1972	Tolay Creek, California	Salt marsh phanerogams	Harvest
Disraeli, 1977	Bellingham Bay, Washington	Salt marsh phanerogams	Harvest, maximum biomass
Eilers, 1975	Nehalem Bay, Oregon	Salt marsh phanerogams	Harvest, modified Milner and Hughes, 1968
Eilers, 1979	Nehalem Bay, Oregon	Salt marsh phanerogams	Harvest, modified Smalley, 1959
Eilers, 1981	Sweetwater River Estuary, Los Penasquitos Lagoon, Upper Newport Bay, Bolsa Bay, California	Salt marsh phanerogams	Harvest
Gallagher and Kibby 1981	Siletz Bay, Oregon	Carex lyngbvei	Harvest, Lomnicki et al., (1968) modification of Wiegert and Evans, 1964
Herrmann, 1971	Grays Harbor Estuary, Washington	Sediment associated microalgae	Oxygen production
Hoffnagle, 1980	Coos Bay, Oregon	Salt marsh phanerogams	Harvest, Wiegert and Evans, 1964
Kibby, et al., 1980	Oregon	Salt marsh phanerogams	Harvest, Lomnicki et al., (1968) modification of Wiegert and Evans, 1964
Kistritz and Yesaki, 1979	Fraser River Estuary, British Columbia	Salt marsh phanerogams	Harvest, maximum biomass
Mahall and Park, 1976	San Francisco Bay, California	Salt marsh phanerogams	Harvest, maximum biomass
Miller, 1977	Grays Harbor Estuary, Washington	Eelgrass	Harvest
Pamatmat, 1968	False Bay, Washington	Sediment associated microalgae	Oxygen production
Phillips, 1972	Washington	Eelgrass	Harvest
Pomeroy, 1977	Squamish River Estuary, British Columbia	Benthic macro and microalgae	Carbon-14, oxygen production
Pomeroy and Stockner, 1973	Squamish River Estuary, British Columbia	Benthic macroalgae	Oxygen production
Rountree, 1978	Grays Harbor Estuary, Washington	Salt marsh phanerogams	Harvest, maximum biomass
Smith, et al., 1976	Grays Harbor Estuary, Washington	Eelgrass	Harvest
Stockner and Cliff, 1979	Vancouver Harbor, British Columbia	Phytoplankton	Carbon-14
Stockner, et al., 1979	Strait of Georgia, British Columbia	Phytoplankton	Carbon-14
Westley, 1967	Grays Harbor Estuary, Washington	Phytoplankton	Carbon-14

TABLE 1 (con.)

Author and Date	Area Studied	Assemblage Studied	Method
Westley and Tarr, 1965	Grays Harbor Estuary, Washington	Phytoplankton	Carbon-14
Yamanaka, 1975	Fraser River Estuary, British Columbia	Salt marsh phanerogams	Harvest, maximum biomass
Zedler, 1980	Tijuana Estuary, California	Benthic macro and microalgae	Oxygen production
Zedler, et al., 1978	Tijuana Estuary, California	Benthic macro and microalgae; salt marsh phanerogams	Oxygen production; harvest, Smalley, 1959
Zedler, et al., 1980	Tijuana Estuary, California	Salt marsh phanerogams	Harvest, Smalley, 1959

Salicornia virginica located near Ocean Shores on the northwest shore of the mouth of the estuary (figure 2). A site dominated by Triglochin maritimum located along the north channel near the city of Hoquiam was also sampled. Although Rountree does not discuss his results, his data represent the only data from Grays Harbor from which marsh plant productivity can be estimated.

Available reports on estuarine vascular plant productivity in Washington State are few (table 1). Berg et al. (1975, 1980) sampled marsh community structure and productivity in Nisqually Delta in southern Puget Sound. They calculated total annual net productivity of 12 plant associations in the delta, and present data on live and dead biomass for each taxon within each association on a monthly basis from May through October 1975. Disraeli (1977) studied marsh plant communities in Bellingham Bay. He documents changes in biomass of six associations from the period May through September 1976. An extensive study in Puget Sound by Phillips (1972) contains productivity values for the eelgrass Zostera marina. Bayer (1979), Smith et al. (1976), and Miller (1977) present shoot growth data for Zostera marina in Yaquina Estuary, Oregon, and Grays Harbor, respectively, but these values are not easily converted into productivity on a dry weight/area basis.

Studies presenting productivity values for estuarine angiosperms have been conducted in the Fraser River Delta, British Columbia (Yamanaka, 1975; Kistritz and Yesaki, 1979), in Oregon (Eilers, 1975, 1979; Hoffnagle, 1980; Kibby et al., 1980; Gallagher and Kibby, 1981), and California (Mahall and Park, 1976; Zedler, 1980; Zedler et al., 1978; Zedler et al., 1980; Eilers, 1981). Among these, the most comprehensive study in the Pacific Northwest is that by Eilers (1975). He documented changes in marsh plant biomass bimonthly from May through September 1972. Eilers harvested plants in quadrats placed along seven transects which extended from extratidal marsh (above 2.76 m relative to MLLW), down to intertidal marsh (below 2.76 m). Eilers lists the mean biomass for 36 taxa within 107 stands (sites) over the period sampled.

Production by benthic algae is also an important component of the primary productivity in Pacific Northwest estuaries (Pomeroy, 1977; Naiman and Sibert, 1978). Of the six studies on benthic algal productivity in west coast estuaries, the most comprehensive one is that by Pomeroy (1977). Pomeroy evaluated the sources and levels of carbon fixation in the Squamish River Delta, British Columbia.

Sieburth (1969) and others have shown that a large proportion of the carbon fixed by benthic macroalgae is exuded from live plants as dissolved organic matter. He found that approximately 30 percent of the total carbon or 40 percent of the net carbon fixed per day is exuded by intertidal populations of the brown fucoid alga *Fucus vesiculosus* L. The algal associations studied by Pomeroy (1977) exuded from 0 to 30 percent of net carbon (as dissolved organic matter) they fixed. Extracellular organic matter produced by benthic algae must be taken into account when primary productivity and inshore food chains are considered (Sieburth, 1969). Exudation may represent the primary pathway of dispersal of organic material produced by estuarine algae (and higher plants) with low turnover rates such a perennial algae.

Carbon Input. The flux (i.e., sources and sinks) of organic carbon has been evaluated for Squamish estuary, British Columbia (Pomeroy, 1977); Nanaimo estuary, British Columbia (Naiman and Sibert, 1978); Cook Inlet, Alaska (Chester and Larrance, 1981); and Chesapeake Bay, Maryland (Biggs and Flemer, 1972). Pomeroy estimated that benthic algae accounted for 7 percent of the total carbon input to Squamish estuary as compared to 90 percent by vascular plants and 3 percent by other sources. Naiman and Sibert found that the greatest source of carbon to the mudflat of the estuary was from the Nanaimo River. Chester and Larrance concentrated their investigation on the contribution of phytoplankton to the benthos of Cook Inlet. Using correlations, they concluded that phytoplankton production was of significant importance in accounting for the high level of secondary production in a bay located in the outer portion of the inlet. Biggs and Flemer showed that, of the

405×10^6 kgC/yr reaching the upper portion of Chesapeake Bay, 370×10^6 kgC (91 percent) was from the Susquehanna River. In contrast, virtually all of the 273×10^6 kgC/yr recorded in the middle portion of the Bay was contributed by phytoplankton. Sinks for the carbon included sediments, benthic respiration, water column respiration, and export.

FIELD STUDY

Marsh Phanerogam Productivity. Four study sites were established that represent the predominant marsh associations in the estuary (figure 3). A high marsh site was established on the west side of South Bay near the city of Westport (124°05'45" latitude, 46°53'20" longitude). The site contains a dominant cover of *Juncus balticus*. A low marsh site, with a predominant cover of *Triglochin maritimum* and *Salicornia virginica*, was chosen at the southwest portion of South Bay (124°04'55" latitude, 46°51'40" longitude). A site containing a pure stand of *Carex lyngbyei* was established on the north shore of the estuary opposite Moon Island (designated Bowerman Basin) (123°56'35" latitude, 46°59'00" longitude). The fourth site was dominated by *C. lyngbyei* and was located on the eastern shore in a tidally influenced portion of Newskah Creek (123°51'05" latitude, 46°56'54" longitude) (table 2). This site is located approximately 200 meters (m) south of the railroad bridge over the creek.

The productivity of marsh plant assemblages at each site was based on samples collected in April, June, August, and November 1980. The high marsh, low marsh, and Newskah Creek sites were again sampled in January 1981, and the Bowerman Basin site was sampled in February 1981. During each site visit, a $0.25m^2$ quadrat was tossed three to five times. All vegetation occurring within each quadrat was clipped at ground level and placed in labelled plastic bags. In the lab, the material was sorted into live (i.e., green shoots) and dead (i.e., brown shoots) portions, dryed at 90°C to a constant weight, and weighed to the nearest 0.01 gram (g). The percentage cover of each species within each quadrat was visually estimated during the August sampling (table 2). For this study, net areal primary productivity (NAPP) for each assemblage is equal to maximum live weight biomass recorded for the assemblage. This method underestimates NAPP of marsh plants (Lithurst and Reimold, 1978).

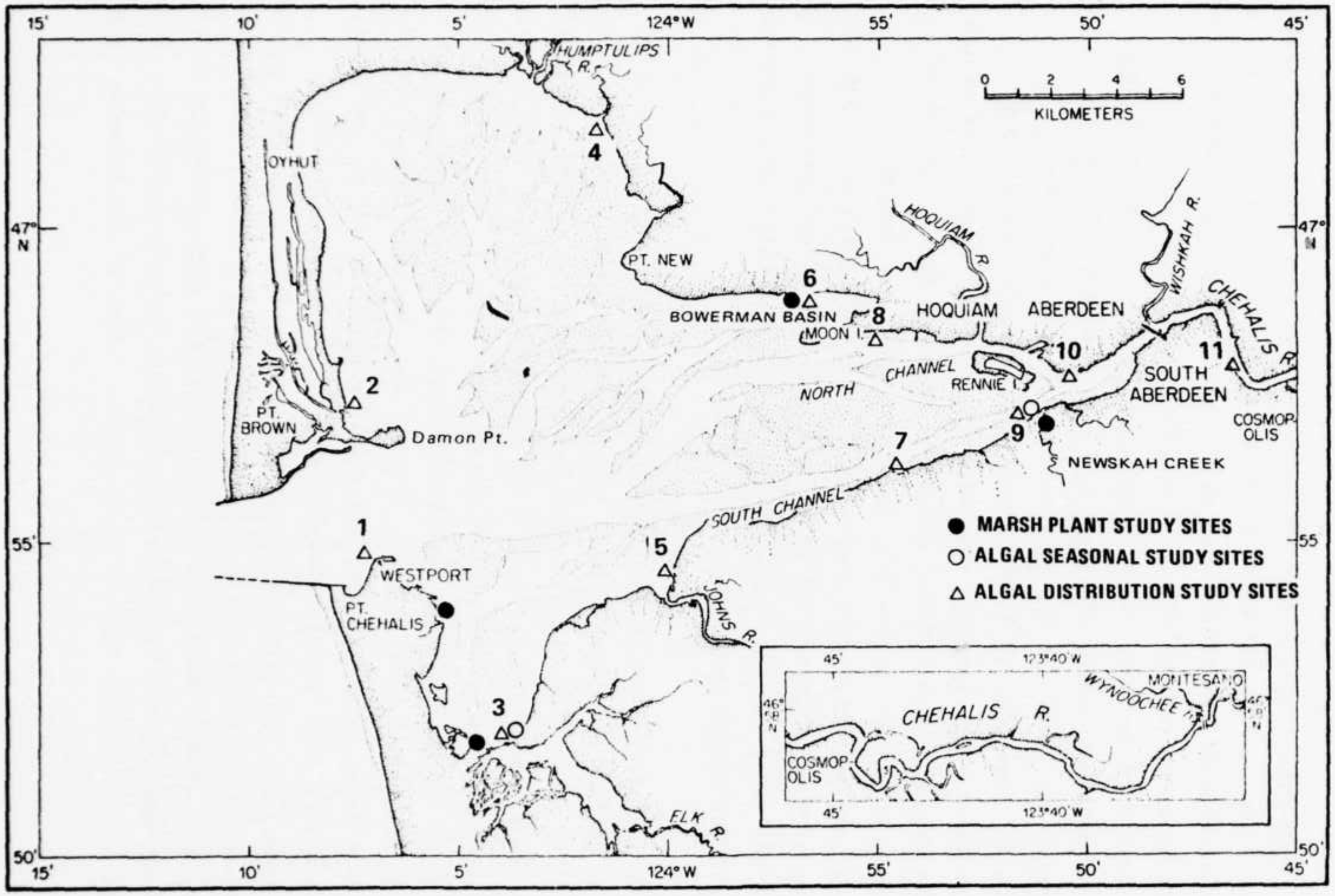

Figure 3. Grays Harbor Study Sites

TABLE 2

AVERAGE PERCENTAGE COVER OF MARSH PLANTS
AT EACH SITE IN AUGUST 1980

Species	Site			
	High Marsh	Low Marsh	Newskah Creek	Bowerman
Juncus balticus	81			2
Stelleria humifusa	5			
Atriplex patula	12			
Potentilla pacifica	2			
Carex lyngbyei			100	98
Triglochin maritimum		62		
Salicornia virginica		35		
Distichlis spicata		3		

Note: N = 5.

Benthic Algal Distributions. The composition and abundance of benthic algal assemblages was sampled along the perimeter of the estuary at 11 sites extending from the groins at Westport to a boat ramp in Cosmopolis (figure 3 and table 3). Due to the high degree of habitat variability among the sites, several methods were employed to sample algal abundances. The general method used consisted of extending a tape measure from a point above the intertidal zone vertically down to the water's edge during low tide. A $0.1 m^2$ quadrat was placed at regular intervals along the transect, and the cover of each species occurring within the quadrat was visually estimated. In areas where transect sampling was not feasible (e.g., across a 1.5-km-wide mudflat in North Bay), a visual estimate was made of the cover of algal taxa within the vicinity of a site. Specimens of species difficult to identify in the field were collected and identified later in the laboratory using a microscope and taxonomic keys. The 11 sites were sampled on 26 August 1980.

Benthic Algal Productivity. The productivity of three species of green algae (i.e., *Enteromorpha clathrata* var. *crinita*, *E. linza*, *E. intestinalis*), a species of brown algae (i.e., *Fucus distichus* ssp. *edentatus*), two species of red algae (i.e., *Polysiphonia hendryi* var. *deliquescens*, *Porphyra sanjuanensis*) and a complex of tube dwelling and filamentous diatom species was measured. These taxa are among the most abundant and conspicuous algal taxa in the estuary, although some (e.g., *E. clathrata* var. *crinita*, *P. hendryi* var. *deliquescens*) are present only during some seasons.

The methods of Littler and Murray (1974) were primarily used for algal productivity measurements. A small portion or an entire individual (range = 0.03 to 0.91g, table 4) of each taxon was placed in a 300 ml biochemical oxygen demand (BOD) bottle containing water. Dark bottles containing the algae were prepared by wrapping the bottles with aluminum foil. Three to four light bottle and two to four dark bottle replicates were prepared for each taxon. The same number of blanks (i.e., water

TABLE 3

THE SAMPLING SITES FOR BENTHIC
ALGAL DISTRIBUTIONS

1. Westport Jetty (WPJ)
2. Ocean Shores Marina (OSM)
3. Elk River Bridge (ERB)
4. Chenois Creek (CC)
5. Johns River (JR)
6. Bowerman Basin (BB)
7. Salt Marsh Control (SMC)
8. North Channel (NC)
9. Salt Marsh Establishment Site (SME)
10. Cow Point (CP)
11. Cosmopolis Boat Launch (CBL)

TABLE 4

BIOMASS OF ALGAL MATERIAL USED
IN THE PRODUCTIVITY EXPERIMENTS

TAXA	JUNE Mean Dry Weight (grams)	JUNE Range (grams)	AUGUST Mean Dry Weight (grams)	AUGUST Range (grams)	April Mean Dry Weight (grams)	April Range (grams)
diatom	0.31	0.06 - 0.94	--1/	--	--	--
Enteromorpha clathrata var. *crinita*	--	--	0.07	0.03 - 0.11	--	--
E. linza	0.14	0.10 - 0.19	--	--	--	--
E. intestinalis	--	--	0.38	0.30 - 0.52	0.18	0.08 - 0.35
Fucus distichus ssp. *edentatus*	0.19	0.12 - 0.23	0.22	0.12 - 0.32	0.09	0.05 - 0.15
Polysiphonia hendryi var. *deliquescens*	--	--	--	--	0.10	0.05 - 0.15
Porphyra sanjuanensis	--	--	--	--	0.19	0.11 - 0.38

1/-- = not determined.

with plankton only) were also prepared. Initial dissolved oxygen (DO) concentration was determined using the mean of Winkler titrations from three BOD bottles treated as above but not containing algae. The bottles were placed horizontally in shallow pools (i.e., 3 to 5 inches deep) and allowed to incubate for 3 to 3.5 hours between 1000 and 1400 hours. The final DO in each bottle was then determined after removal of the algae. Each algal specimen was spread flat on a piece of clear plastic and photocopied. The area covered by the thallus was then determined using a polar planimeter. The asssumption in using two-dimensional thallus area is that, at any one time, only a single side of a thallus faces sunlight (Littler et al., 1979). Finally, the specimens were dried at 90°C and weighed to the nearest 0.01 g.

The DO valves were converted to g C fixed/m^2 of thallus/hour and mg C fixed/g of thallus/hour using the formulas in Strickland (1960) and a photosynthetic quotient value of 1.2. For each taxon, the replicates for respiration were averaged and this value was added to the individual values for each light bottle (net production) replicate for the same species. The average of these totals was used as an estimate of mean gross productivity.

The total yearly productivity for each taxon was determined using data on the above rates, total aerial coverage of the taxon in the estuary, and an estimate of the time the taxon is present in the estuary. The formula used was:

$$P_T = \frac{(P_N)(H)(D)(C)}{1{,}000 \text{g/kg}}$$

P_T = productivity in kg C/yr;

P_N = productivity in g C/m^2/hr;

H = Correction to daily rate = ($\bar{x}$ day length during the period of presence)(hourly productivity rate) - ($\bar{x}$ night length)(hourly respiration rate);

D = approximate number of days the taxon was present in the estuary; and

C = total cover of the taxon in the estuary or in the area of concern.

An estimate of D is based on approximately monthly observations. The values of D used for Fucus distichus, Enteromorpha linza, diatoms, E. crinita, E. intestinalis, Polysiphonia hendryi var. deliquescens, and Porphyra sanjuanensis were 365, 120, 365, 90, 120, 90, and 90, respectively. Calculation of H follows the methods of Littler et al. (1979).

Benthic Algal Seasonality. Temporal changes in algal assemblages were followed approximately bimonthly between September 1980 and June 1981 at the site near Elk River (ER) and the salt marsh establishment (SME) site (figure 3). These sites represent inner and outer harbor environments (figures 4 and 5), and the data are necessary to document seasonal variations in abundance of the major macroalgal taxa. At the Elk River site, a transect was extended vertically down the boulder riprap from a point above the intertidal zone down to the mud (approximately at +3 feet relative to MLLW). The taxon occurring within a $0.06m^2$ plexiglass quadrat placed at 1-foot intervals along the transect tape were recorded. The cover of each taxon was estimated by tallying the proportion of 20 randomly located points within each quadrat that overlayed the taxon. A total of 23 quadrats were sampled along the transect. Five $0.06m^2$ quadrat sites were permanently marked in the densest portion of the Fucus distichus ssp. edentatus bed on the boulder wall. The cover of Fucus was estimated by projecting color 35mm slides of each quadrat onto a grid of 20 random points, and recording the proportion of points covered by Fucus. The cover of Vaucheria was sampled by extending a tape measure across the middle of an approximately 10m-diameter patch of this species. Photographic samples of five permanently located $0.06m^2$ areas were treated similarly to the permanent Fucus quadrat samples.

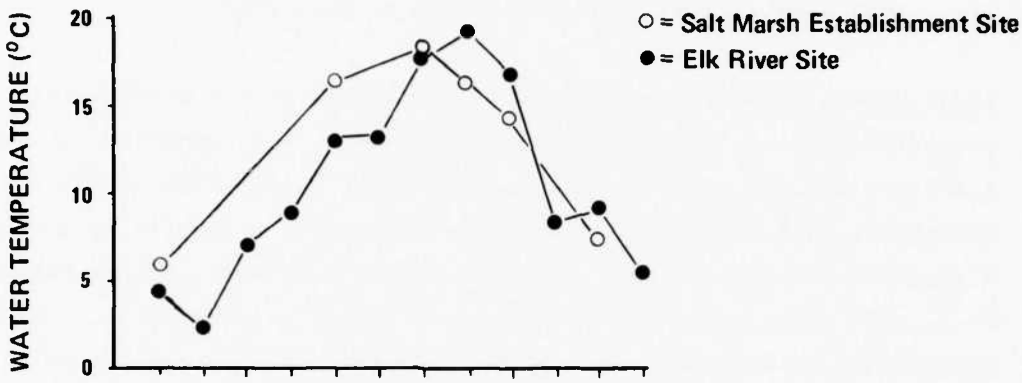

Figure 4. Temporal Changes in Surface Water Temperature Near the Algae Study Sites. Data from Collias and Loehr (1981)

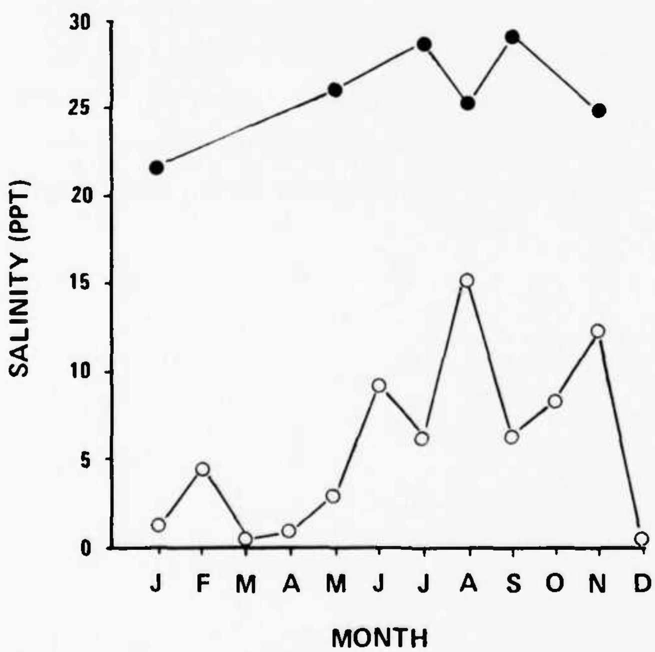

Figure 5. Temporal Changes in Surface Water Salinity Near the Algae Study Sites. Data From Collias and Loehr (1981)

At the SME site, a transect extending down an extensive tree root system was sampled in the same manner as the transect at Elk River. Thirty-two quadrats were sampled along the transect at the SME site. Five permanent *Fucus* sample areas and five permanent *Enteromorpha*/*Blidingia* areas were also sampled photographically at this site.

Algal Growth Rates. The persistence and growth of the predominant perennial species, *F. distichus* ssp. *edentatus*, was documented at the Elk River and SME sites using tagged plants. *Fucus* fixes carbon but may contribute this carbon to the aquatic environment primarily by exuding dissolved carbon containing compounds. Tagging plants allowed estimates to be made of the rate of loss of plants to the estuary, thus providing an estimate of the amount of carbon contributed as particulate matter by this species.

Twenty-five plants were tagged at each site in September 1980. The tags consisted of a numbered, thin aluminum plate (approximately $1cm^2$) which was attached to the base of the plant with a thin piece of stainless steel wire. The length of the longest frond, as measured from the top of the hold fast to the tip of the longest dichotomy, was recorded for each plant in September and November 1980, and February, April, and June 1981.

DATA REDUCTION

Vascular Plants. It was necessary to convert productivity rates for marsh plants and *Zostera* spp. into the same units as algal productivity rates for comparative purposes. Further, it was necessary to compute the total amount of carbon that might be expected to reach the estuary from each community type. Eilers (1975) showed that the amount of marsh plant detritus reaching the aquatic environment decreased with increasing elevation. The data of Smith et al. (1976) was used to provide an estimate of total cover of each taxon in the estuary and to group taxa into marsh types. The proportion of the amount of biomass reaching the estuary from each marsh type was estimated using the data in Eilers (1975). Data on productivity rates for each species were gathered from the literature on marsh productivity in Pacific Northwest estuaries (reviewed above) and from that gathered by the present study. In taking productivity values from the literature, rates for species in similar vegetation assemblages as those listed by Smith et al. were used.

The following calculations were made:

$$P_N = \frac{(P)(C)(Q)}{1{,}000\text{g/kg}}$$

P_N = total estuarine productivity of marsh species N in KgC/yr;

P = productivity of species N in g/m^2/yr;

C = total cover of species N in the estuary; and

Q = conversion of productivity rate from dry weight biomass to carbon = 0.45 (Westlake, 1963; Kistritz and Yesaki, 1979).

The total productivity rate (P_{tm}) of each community type was calculated as:

$$P_{tm} = (P_m)(t)$$

P_m = sum of productivity rates for all species in a marsh type; and

t = proportion of this productivity that can be expected to reach the aquatic environment.

Fluvial Sources. No data are available on allochthonous organic matter entering Grays Harbor Estuary. Therefore, it was necessary to use the data on the allochthonous contribution of dissolved organic carbon (DOC), fine particulate organic carbon (FPOC), and large particulate organic carbon (LPOC) of Naiman and Sibert (1978). Their study was conducted in the Nanaimo Estuary, British Columbia. Although somewhat smaller than the main tributaries emptying into Grays Harbor Estuary, the Nanaimo River flows through the same type of terrain and forest community as occurs in the vicinity of Grays Harbor. The yearly contribution of carbon from fluvial sources was based on a conversion ratio of flow volumes between the Grays Harbor Estuary tributaries and the Nanaimo River, which was multiplied by the total amount of carbon reaching Nanaimo Estuary.

Phytoplankton. The data of Westley and Tarr (1965) for Grays Harbor was used to estimate net phytoplankton productivity. Yearly rates were calculated by multiplying hourly rates by 4 hours (for intertidal areas) and 8 hours (for channel areas), and then by 365 days. The assumptions are that phytoplankton photosynthesis takes place for an average of 8 hours/day over the year, and that the time allowable for photosynthesis by phytoplankton in intertidal areas is half of that in the channel areas.

Oceanic Input. Phipps and Scheideggar (1974) reported that a large proportion of the sediments in the outer one-third of the estuary are of oceanic origin. Data on volatile solids (i.e., a measure of organic content of sediments) content in the sediments indicate that the amount of carbon present is very low (i.e., less than 1.8 percent) (Phipps and Schermer, unpublished data) (figure 6). Therefore, oceanic sources of carbon are not considered in the present study, which is consistent with similar studies.

Productivity by Estuary Region. To aid in interpreting the relative contribution of each carbon source to various areas, the estuary was divided into nine regions (figure 7 and table 5). The regions were arbitrarily determined but represent divisions based on geophysical conditions. The regions are groupings of "junctions" used in developing a numerical model of water quality in the estuary (Cleland, 1978). The area of each carbon source within each region was determined using estimates presented in the literature and observations made during the present study.

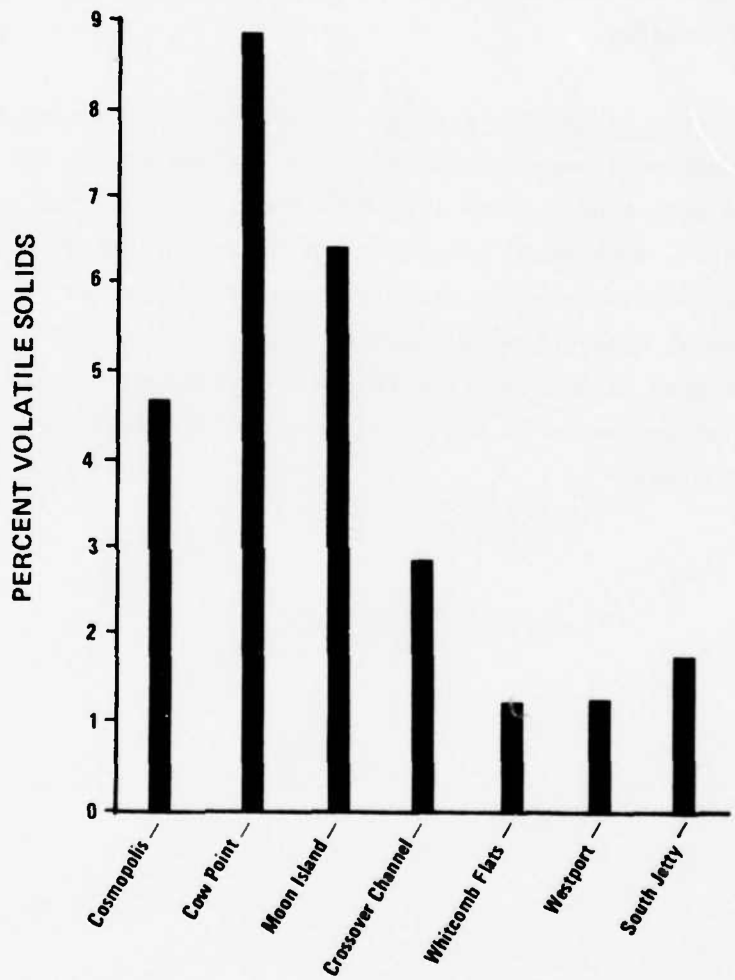

Figure 6. Volatile Solids Content of Surface Sediments Taken at Sites Adjacent to the Navigation Channel (Seattle District, Unpublished Data)

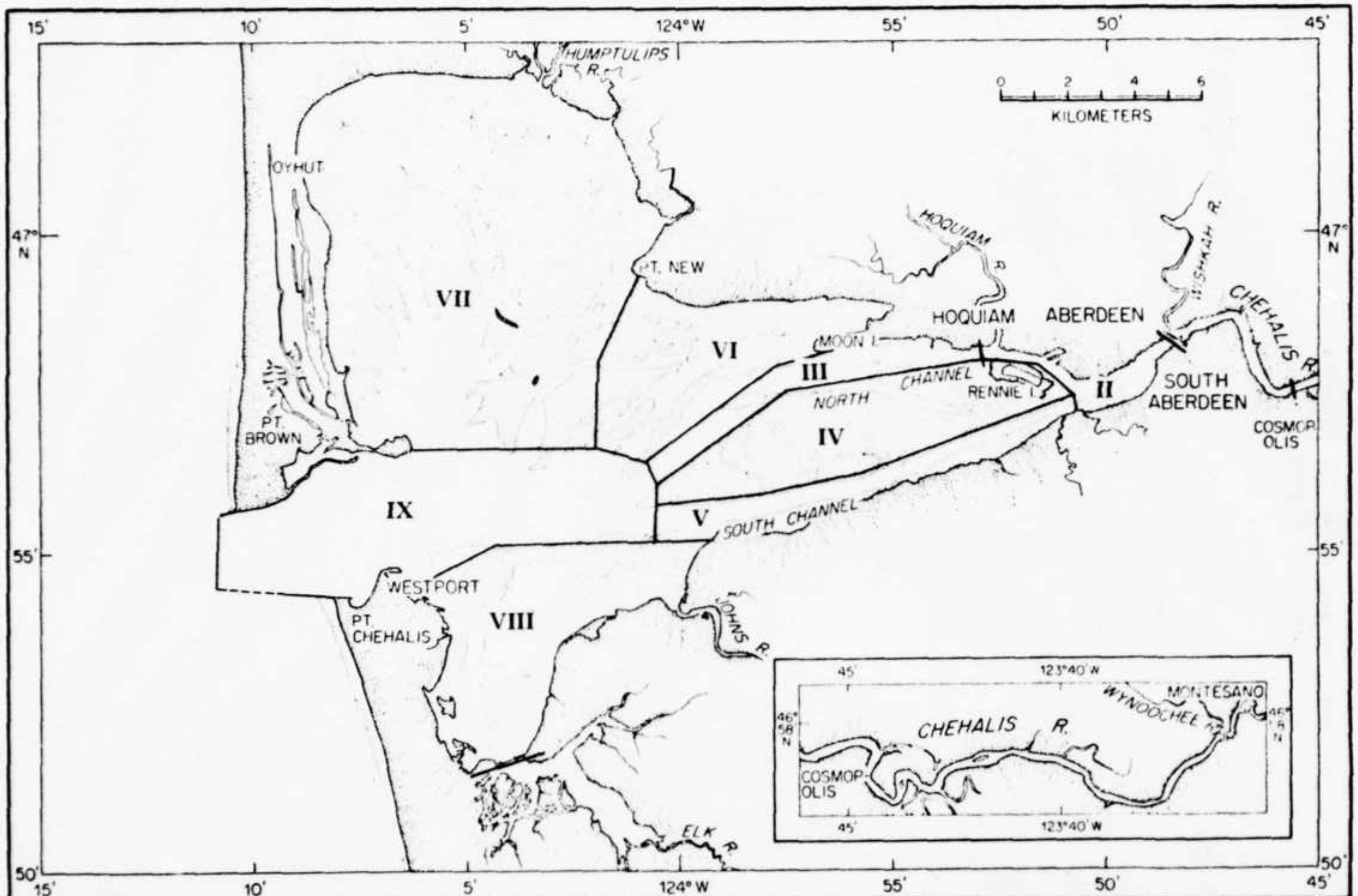

Figure 7. Grays Harbor Regions I Through IX

TABLE 5

SURFACE AREAS OF THE REGIONS
(See Also Figure 7)

Area No.	Region Name	Surface Area ($X10^6 m^2$)
I	Cosmopolis	1.9185
II	Cow Point	4.4433
III	North Channel	11.7644
IV	Mid Harbor	24.8780
V	South Channel	8.7700
VI	Bowerman	24.3353
VII	North Bay	95.6899
VIII	South Bay	32.6192
IX	Entrance	36.0344

RESULTS AND DISCUSSION

Marsh Phanerogams. Live biomass peaked in June at sites in the low marsh, sedge marsh, and freshwater marsh and in August at the site in the high marsh (figure 8). Live biomass remained high in the former three sites through August, while dead standing biomass increased slightly between June and August. Peaks in dead biomass occurred in winter (January and February) and early spring (April).

The greatest amount of live biomass was found at the sedge marsh (*Carex lyngbyei*) (700.20g/m^2) in Bowerman Basin (figure 8). This site was followed by the *C. lyngbyei* stand sampled in Newskah Creek (491.64g/m^2) the high marsh near Westport (425.04g/m^2), and the *Triglochin*/*Salicornia* low marsh near Elk River (369.92g/m^2).

Observations showed that there had been considerable dieback and export of biomass from the freshwater marsh and sedge marsh by November. The export by tidal action and riverflow was essentially complete by the January and February samplings at these sites, and it is assumed that all of this material reached the aquatic system. Export from the low marsh was evident in November and complete by January. A system of tidal channels surrounds this site, and most of the export to the estuary would be through these channels. Very little material was observed to be decaying within the low marsh. Samples of unattached material in the plots within the high marsh consisted of an approximately 10-cm deep mat of marsh vegetation in various stages of decay, which indicates that very little of the biomass produced in the high marsh reaches the aquatic environment. Leachate from this material may reach the estuary in significant quantities, however.

Benthic Algal Distribution. Twenty-three taxa of macroalgae were encountered during the study (table 6). The number of taxa generally decreased moving from the mouth of the harbor near Westport to the site

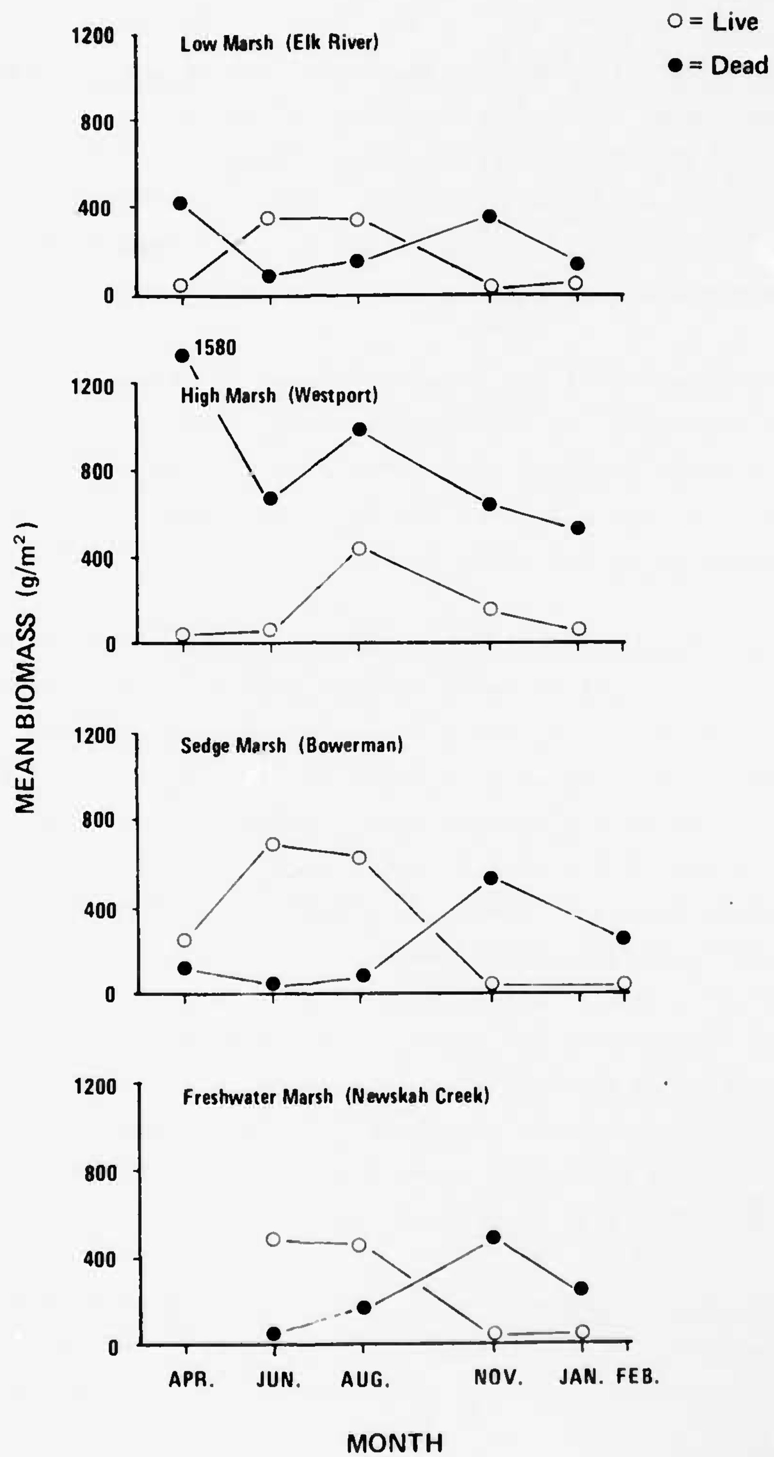

Figure 8. Temporal Changes in Mean Dry Weight Biomass of Marsh Phanerogams in 1980-1981

TABLE 6

DISTRIBUTION OF ALGAL TAXA IN GRAYS HARBOR

TAXA	WPJ[1/] 1	OSM 2	ERB 3	CC 4	JR 5	BB 6	SMC 7	NC 8	SME 9	CP 10	CBL 11	HABITAT
Tube Dwelling Diatoms		X[2/]		X		X						Rocks, debris, epiphytic.
Vaucheria longicaulis Hopp.			X			X		X				Dense, dark green patches in mud.
Chlorophyta												
Blidingia minima var. *subsalsa* (Kjellm.) Scag.									X			on logs and tree roots, high intertidal.
Enteromorpha clathrata (Roth) Grev. var. *clathrata*					X				X		X	Rocks or unattached in mats.
E. clathrata var. *crinita* (Roth) Hauck		X	X			X						Rocks or unattached in mats.
E. flexuosa (Roth) J.Ag.		X										Rocks, high intertidal.
E. intestinalis (L.) Link		X	X				X	X	X	X		Rocks, epiphytic, high intertidal.
E. linza (L.) J.Ag.		X	X									Rocks.
Monostroma oxysperma (Kutz.) Doty			X									Rocks, mid intertidal.
Rhizoclonium riparium (Roth) Harvey				X								Dense mat in mud.

1/See list of sites and their abbreviations in table 3.
2/X = Present

TABLE 6 (con.)

TAXA	WPJ[1] 1	OSM 2	ERB 3	CC 4	JR 5	BB 6	SMC 7	NC 8	SME 9	CP 10	CBL 11	HABITAT
Ulva _expansa_ (Setch.) S. & G.		X	X									Rocks or unattached.
_U._ _fenestrata_ P. & R.												Drift.
_U._ _rigida_ C.Ag.	X											Rocks, high intertidal.
Phaeophyta												
Alaria _marginata_ Post. & Rupr.	X											Rocks, low intertidal.
Fucus _distichus_ ssp. _edentatus_ (de la Pyl.) Pow.		X	X	X			X		X	X		Rocks, epiphtyic on _Salicornia_, in space to dense beds.
Petalonia _fascia_ (Mull) Kuntze	X											Rocks, mid-low intertidal.
Ralfsia sp.	X											Rocks, high-low intertidal.
Rhodophyta												
Gigartina _agardhii_ S. & G.	X[2]											Rocks, mid-intertidal.
_G._ _papillata_ (C.Ag.) (J.Ag.)	X											Rocks, high-low intertidal.
Iridaea _cordata_ (Turn.) Bory	X											Rocks, mid-low intertidal.
Microcladia _borealis_ Rupr.	X											Rocks, mid-intertidal.
Polysiphonia _hendryi_ var. _deliquescens_ (Hollenb.) Hollenb.			X									Unattached, in mats on mud and rocks.

1/See list of sites and their abbreviations in table 3.
2/X = Present

TABLE 6 (con.)

TAXA	WPJ[1/] 1	OSM 2	ERB 3	CC 4	JR 5	BB 6	SMC 7	NC 8	SME 9	CP 10	CBL 11	HABITAT
Porphyra lanceolata (Setch. & Hus) Smith	X	X	X									Rocks, high-mid intertidal.
Porphyra sanjuanensis Krishnamurthy			X									Epiphytic on Salicornia
Smithora naiadum (Anders.) Hollenb.			X									Epiphytic on Zostera marina
TOTAL NO. TAXA	9	8	12	3	1	3	2	2	4	2	1	

1/See list of sites and their abbreviations in table 3.

on the Chehalis River near Cosmopolis, which correlates with a decrease in mean salinity (Loehr and Collias, 1981) (figure 5).

The most widespread species were Enteromorpha intestinalis and Fucus distichus ssp. edentatus. Diatoms evident as tufts or filaments were also widespread and grew on a variety of substrata. Several species of macroalgae were commonly found unattached. Enteromorpha clathrata var. crinita forms dense (e.g., 8 kg dry wt./m^2) skeins which drift along the bottom with tidal currents. This species was found in greatest abundance in late summer and can reach high local densities. Free-floating, large (up to 30cm long) individuals of the filamentous red alga Polysiphonia hendryi var. deliquescens were common in spring near Elk River. Fucus, along with Porphyra sanjuanensis occur attached to mid intertidal plants of Salicornia virginica in many areas of the outer harbor. Species growing in dense mats in sand include Vaucheria longicaulis and Rhizoclonium riparium. Vaucheria forms hummocky, dark green mats throughout the estuary. Rhizoclonium was common along a channel at the mouth of Chenois Creek in North Bay.

Benthic Algal Seasonality. Total algal cover varied with season on the transects at Elk River and SME site (figure 9). Cover peaked in autumn at Elk River and in spring at SME. The bulk of algal cover is made up of Fucus at both sites.

The cover of Enteromorpha/Blidingia complex at SME also changed substantially with season (figure, 9B). Fucus cover showed little variation at either site (figure 10, A, B), with most plants persisting (i.e., little turnover) throughout the study. The patch of Vaucheria sampled appeared to die after the autumn sampling, although nearby patches persisted throughout the year (figure 10A). There was no apparent explanation for the dieback of this particular patch of Vaucheria.

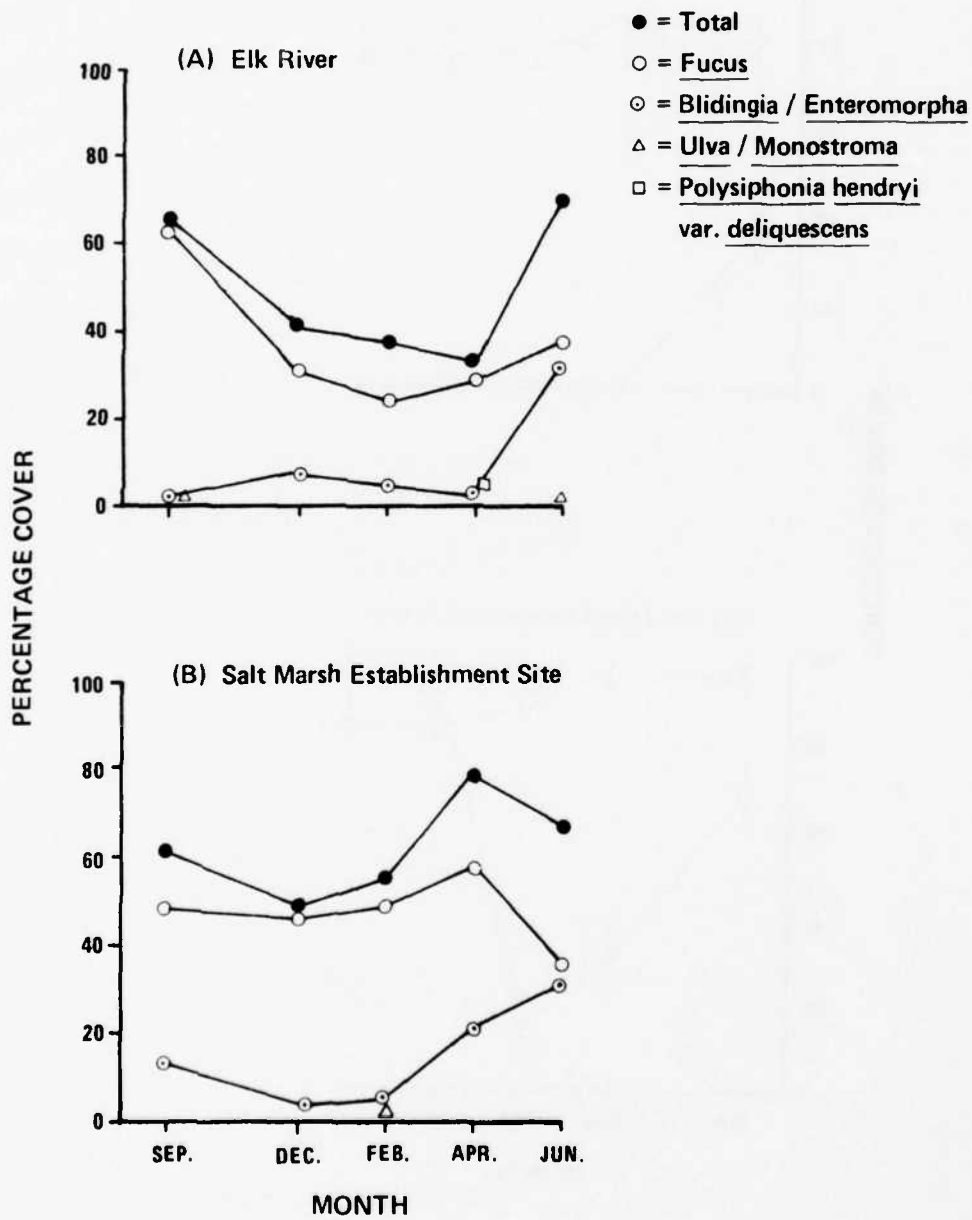

Figure 9. Temporal Changes in Mean Algal Cover at the Two Transect Sites (1980-1981)

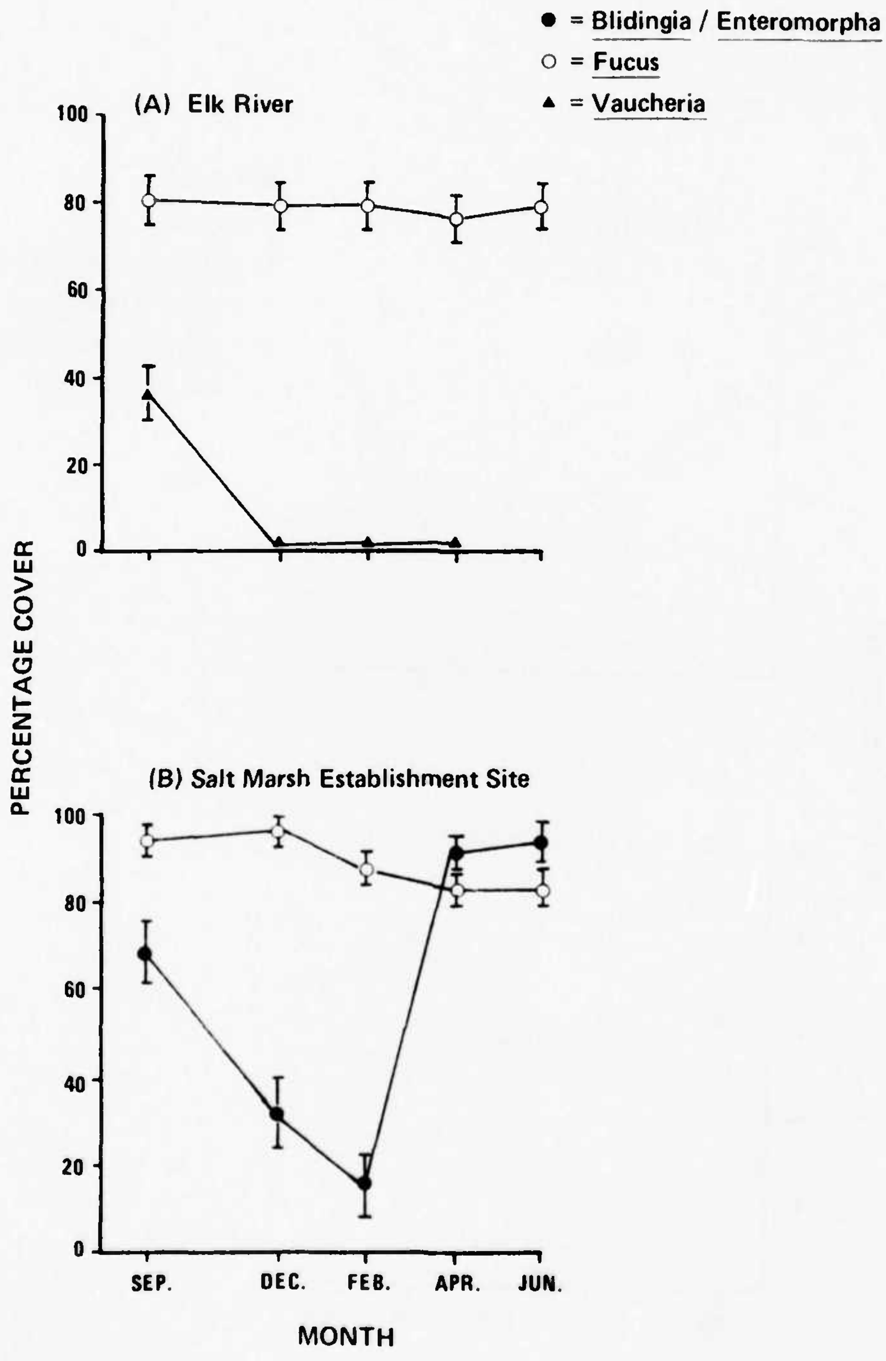

Figure 10. Temporal Changes in Mean Algal Cover in Permanent Plots (1980-1981)

N = 5 for Each Taxon. The 95 Percent Confidence Intervals are Calculated Using the Method of Snee (1974)

Algal Growth Rates. *Fucus* grows fastest in late winter-early spring (figure 11). Further, the data indicate that over the winter (i.e. between September and April) approximately 50 percent of the population is lost to the estuary (figure 12). The apparent disagreement between cover and tagged plant estimates of turnover suggest that cover data (figure 10, A, B) may not show gains and losses of members of the population.

Benthic Algal Productivity. Mean algal productivity rates determined during this study are given in tables 7 and 8. Most of the rates were within the range of values for other marine areas, with the notable exception of *E. clathrata* var. *crinita* (table 9). This alga photosynthesized at a rate at least three times that reported in the literature surveyed (including several references not shown in table 9).

Primary Production in the Estuary. Data on productivity rates and total yearly productivity for aquatic vegetation in the estuary are summarized in table 10. The differences among species were related both to differences in productivity rates and areal coverage. The highest rates were generally found among benthic algae and eelgrass.

The high values for relatively inconspicuous sediment microalgae (table 10) suggests a high turnover rate for this assemblage. Turnover rates for macroalgae and eelgrass are less, and rates for marsh phanerogams are probably least (i.e., once per year when exudation is not considered). Turnover rate (i.e., the rate at which biomass is produced and dies or is removed from an area) is important when considering sources of carbon available to an estuarine ecosystem.

Contributions of Organic Carbon. The amount of carbon fixed that reaches the estuary depends upon the location of the source and the availability of a route to the estuary from the source. If a vegetation type exists in the mid to low intertidal zone, most of the biomass produced probably gets to the aquatic environment in a relatively short

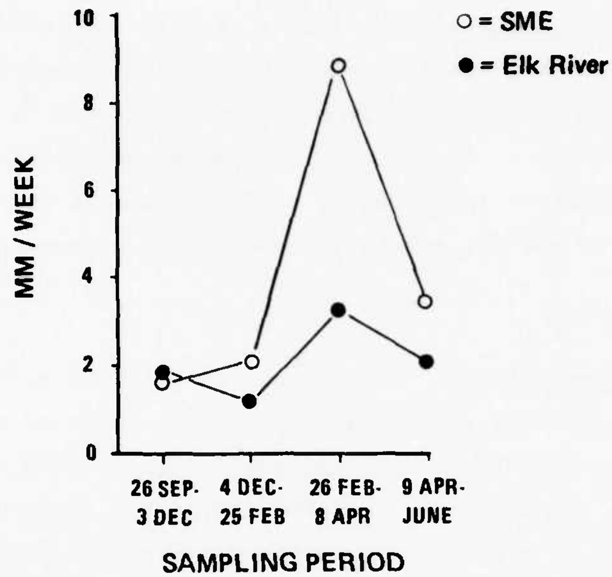

Figure 11. Mean Weekly Increase in Fucus Frond Length.

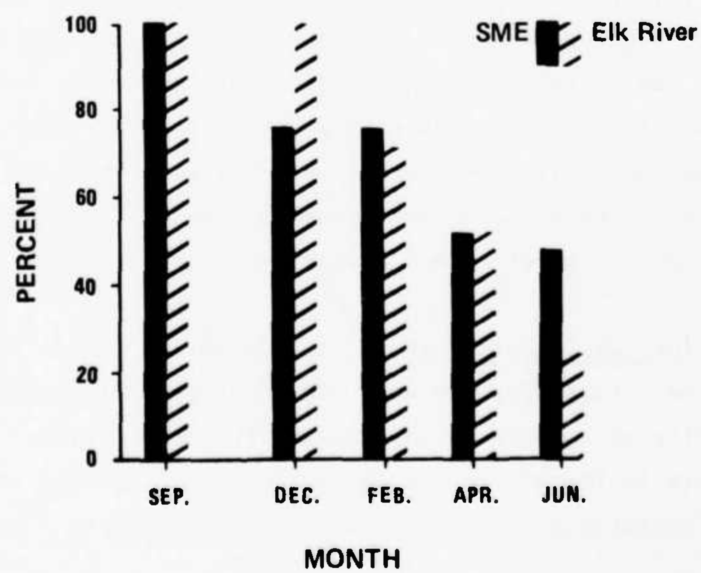

Figure 12. The Percentage of Tagged Plants Remaining at Each Site During Each Sampling

TABLE 7

MEAN NET PRODUCTIVITY RATES FOR BENTHIC ALGAL TAXA

Taxa	June		August		April	
	$gC/m^2/hr$	mgC/g/hr	$gC/m^2/hr$	mgC/g/hr	$gC/m^2/hr$	mgC/g/hr
diatoms	0.266	1.276	--	--	--	--
Enteromorpha clathrata var. *crinita*	--	--	1.792	31.347	--	--
E. intestinalis	--	--	0.869	2.248	1.179	6.959
E. linza	0.113	6.579	--	--	--	--
Fucus distichus ssp. *edentatus*	0.581	5.254	0.601	3.867	0.311	3.225
Polysiphonia hendryi var. *deliquescens*	--	--	--	--	0.166	7.632
Porphyra sanjuanensis	--	--	--	--	0.090	6.872

Note: -- = not determined.

TABLE 8

MEAN GROSS PRODUCTIVITY RATES FOR BENTHIC ALGAL TAXA

Taxa	June		August		April	
	$gC/m^2/hr$	mgC/g/hr	$gC/m^2/hr$	mgC/g/hr	$gC/m^2/hr$	mgC/g/hr
diatoms	0.502	2.644	--	--	--	--
Enteromorpha clathrata var. *crinita*	--	--	2.044	34.150	--	--
E. intestinalis	--	--	1.342	3.200	--	--
E. linza	0.127	6.970	--	--	--	--
Fucus distichus ssp. *edentatus*	0.654	6.027	0.792	4.996	0.358	3.713
Polysiphonia hendryi var. *deliquescens*	--	--	--	--	0.190	9.488
Porphyra sanjuanensis	--	--	--	--	0.096	7.322

TABLE 9

NET PRODUCTIVITY OF SOME MARINE SYSTEMS

System	Net Productivity	
	gC/M²/hr.1/	mgC/g dry wt./hr.2/
Five intertidal algal populations, Grays Harbor Estuary, Washington	0.11-1.79	1.28-31.35
18 intertidal algal populations, San Clemente Island, California (Littler and Murray, 1974)	0.04-0.34	0.3-3.3
Algal mat under marsh plant canopy, Tijuana Estuary, California (Zedler, 1980)	0.06-0.10	
Phytoplankton, Vancouver Harbor, British Columbia (Stockner and Cliff, 1979)	0.06-0.12	
Marsh fucoids, Flax Pond, New York (Brinkhuis, 1977)		0.5-2.0
Two macroalgal species, Newport Bay, California (Littler, 1979)	0.02-0.16	1.5-11.0

1/Grams carbon per square meter per hour.
2/Milligrams carbon per gram dry weight per hour.

TABLE 10

NET PRODUCTIVITY
OF AQUATIC VEGETATION IN GRAYS HARBOR

Vegetation Type	Net Productivity ($g/m^2/yr$)	Net Productivity ($gC/m^2/yr$)	Reference
Low Silty Marsh		767 1/	
Triglochin maritimum L.	426	192	Rountree, 1978
Salicornia virginica L.	942	424	Rountree, 1978
Spergularia canadensis (Pers.) G. Don	1	0.5	Eilers, 1979 (*S. marina*)
Carex lyngbyei Hornem	50	22.5	Berg, et al., 1975
Deschampsia caespitosa (L.) Beaun	100	45	Hoffnagle, 1980
Distichlis spicata (L.) Greene	184	83	Rountree, 1978
Low Sandy Marsh		979 1/	
Salicornia virginica L.	942	424	Rountree, 1978
Jaumea carnosa (Less) Gray in Torr.	80	36	Rountree, 1978
Triglochin maritimum L.	426	192	Rountree, 1978
Distichlis spicata (L.) Greene	184	83	Rountree, 1978
Atriplex patula L.	3	1.4	Eilers, 1979
Festuca rubra L.	479	216	Eilers, 1979
Plantago maritima L.	2	0.9	Berg, et al., 1975
Glaux maritima L.	38	17	Eilers, 1979
Triglochin concinna Davy	20	9	Rountree, 1978
Sedge Marsh		529 1/	
Carex lyngbyei Hornem	123	554	Present study
Triglochin maritimum L.	426	192	Rountree, 1978
Immature High Marsh		956 1/	
Deschampsia caespitosa (L.) Beauv	100	45	Hoffnagle, 1980
Juncus balticus Willd	364	164	Present study
Distichlis spicata (L.) Greene	762	343	Rountree, 1978
Salicornia virginica L.	48	22	Rountree, 1978
Atriplex patula L.	3	1.3	Eilers, 1979

1/Total for each community type.

TABLE 10 (con.)

Vegetation Type	Net Productivity ($g/m^2/yr$)	Net Productivity ($gC/m^2/yr$)	Reference
Agrostis alba L.	130	58	Hoffnagle, 1980
Carex lyngbyei Hornem.	50	22.5	Berg, et al., 1975
Triglochin maritimum L.	666	300	Eilers, 1979
Mature High Marsh		1,108 1/	
Deschampsia caespitosa (L.) Beauv	344	155	Berg, et al., 1975
Distichlis spicata (L.) Greene	762	343	Rountree, 1978
Grindelia integrifolia	4	2	Berg, et al., 1975
Glaux maritima L.	4	2	Berg, et al., 1975
Salicornia virginica	48	22	Rountree, 1978
Jaumea carnosa (Less) Gray in Torr.	44	20	Rountree, 1978
Triglochin maritimum L.	20	9	Rountree, 1978
Potentilla pacifica Howell	16	7	Berg, et al., 1975
Carex lyngbyei Hornem.	50	22	Berg, et al., 1975
Achillea millefolium L.	427	192	Eilers, 1979
Agrostis alba L.	878	334	Eilers, 1979
Freshwater Marsh		337.5	
Carex lyngbyei Hornem.	750	337.5	Present study
Eelgrass			
Zostera marina L.	--	255-1,460	Phillips, 1972
Z. noltii Hornem.	--	128-730	2/
Phytoplankton	--	110	Westley and Tarr, 1965; see methods also.
Sediment Microalgae	--	584	Mean value from Herrmann, 1971

1/Total for each community type.
2/0.5 times the rates for *Z. marina* used as an estimate. *Z. noltii* blades are approximately one-quarter as wide as those of *Z. marina*.

TABLE 10 (con.)

Vegetation Type	Net Productivity (g/m^2/yr)	Net Productivity (gC/m^2/yr)	Reference
Tube dwelling diatoms	--	759 1/	Present study
Vaucheria sp. *longicaulis* Hopp.	--	250	Mean value from Pomeroy and Stockner, 1976
Benthic Macroalgae			
Blidingia minima var. *subsalsa* (Kjella.) Scag.	--	--	
Enteromorpha clathrata (Roth) Grev. vas. *clathrata*	--	--	
var. *crinita*	--	1,296 1/	Present study
E. flexuosa (Roth) J. Ag.	--	--	
E. intestinalis L. Link	--	826 1/	Present study
E. linza (L.) J. Ag.	--	96 1/	Present study
Monopstroma oxysperma (Kutz.) Doty	--	--	
Rhizoclonium riparium (Roth) Harvey	--	--	
Ulva expansa (Setch.) S. & G.			
U. fenestrata P. & R.	--	--	
Fucus distichus ssp. *edentatus* (de la Pyl.) Pow.	--	1,752 1/	Present study
Polysiphonia hendryi var. *deliquescens* (Hollenb.) Hollenb.	--	120 1/	Present study
Porphyra lanceolata (Setch. & Hus) Smith	--		
Porphyra sanjuanensis (Setch. & Hus) Smith	--	65 1/	Present study
Smithora naiadum (Anders.) Hollenb.	--	--	

1/Units are in per m^2 of thallus area.

time. Tidal channels around vegetation stands enhance export from higher elevations. As mentioned above, exudation of dissolved organic carbon represents an important mode of transport from some species. Information from Sieburth (1969), Pomeroy (1977) and the present study allow an estimate of carbon flux from an abundant perennial alga (i.e., Fucus) in Grays Harbor Estuary. Estimates of the percentage of organic carbon produced by vegetation that reaches the aquatic environment are given in table 11.

Organic carbon contributed by the Chehalis River at Aberdeen represents 84 percent of the total fluvial carbon input to the estuary (table 12). The Johns and Humptulips Rivers are major sources of allochthonous carbon in the mid and outer harbor regions.

Allochthonous material is the primary source of organic carbon to the Grays Harbor estuary (table 13). Eelgrass represents the greatest source of carbon among the primary producers within the estuary, followed by benthic algae, marsh vascular plants, and phytoplankton. Effluents from the pulp and paper industry represent a source of appreciable amounts of organic carbon.

The total yearly estimated carbon input to Grays Harbor (1196×10^6 KgC) is approximately twice that calculated for the northern half of Chesapeake Bay (678×10^6 KgC) (Biggs and Flemer, 1972). In agreement with data from the present study, Naiman and Sibert (1978) showed that allochthonous material was the primary source (73 percent of total) of organic carbon to Nanaimo Estuary, British Columbia.

The relative contribution of carbon from primary producers varies spatially in the estuary (table 13). Among region variation is due primarily to differences in habitat and areal extent of each source in each of the regions. Zostera spp. contributes the greatest amount in six out of the nine regions, and algae is the primary source in the remaining regions. Eelgrass production is most important in regions

TABLE 11

THE PERCENT OF BIOMASS THAT IS EXPORTED TO THE AQUATIC ENVIRONMENT FROM EACH VEGETATION TYPE

Vegetation Type	Export Percent 1/
Low Silty Marsh	100
Low Sandy Marsh	100
Sedge Marsh	100
Immature High Marsh	50
Mature High Marsh	5
Freshwater Marsh	100
Eelgrass	100
Phytoplankton	100
Benthic Annual Algae	100
Benthic Perennial Algae (*Fucus*)	80

1/Estimates are based on observations from the present study, elevation data in Smith et al. (1976), and export data in Eilers (1975).

TABLE 12

AVERAGE ANNUAL FLOW RATES AND ORGANIC CARBON LOADS FOR RIVERS TRIBUTARY TO GRAYS HARBOR ESTUARY. FLOW RATE INFORMATION IS FROM U.S. GEOLOGICAL SURVEY (1955, 1962, 1964) AND BATTELLE (1973).

Region	Average Flow ($m^3 \times sec^{-1}$)	Organic Carbon ($\times 10^6$ kg x Load yr^{-1})1/
Inner Harbor		
Chehalis River at Aberdeen2/	310	753
Wishkah River near Wishkah	23/	5
East Fork Wishkah River downstream of Wishkah	0.54/	1.2
Hoquiam River near Hoquiam	0.63/	1.5
Miscellaneous		
Little Hoquiam River	0.1	0.2
Newskah Creek	1.3	0.2
Charley Creek	0.8	1.9
Johns River	13	32
Chapin Creek	0.04	0.1
Campbell Creek	0.04	0.1
Indian Creek	0.06	0.1
Stafford Creek	0.04	0.1
O'Leary Creek	0.12	0.3
North Bay		
Humptulips River near Humptulips	38	92
Miscellaneous		
Big Creek	1.15/	3
Burg Slough	0.04	0.1
Chenois Creek	0.145/	0.3
Grass Creek	--	--
South Bay		
Elk River	0.76/	2
Total		893.1

1/Based on a conversion factor calculated from Naiman and Sibert (1978) (see methods section).
2/See Loehr and Collias (1981) for conversion to flow at Aberdeen.
3/Based on July-October 1942-1943 only.
4/Based on July-October 1942 only.
5/Based on single observation only.
6/Based on estimation (Battelle, 1974) using drainage area and precipitation as parameters.

TABLE 13

ORGANIC CARBON CONTRIBUTIONS (x 10^6 KgC/yr) OF VARIOUS SOURCES WITHIN EACH REGION.

(Percentage contributed by each source to the total for each region is in parentheses.)

Source	Region									
	Cosmopolis (I)	Cow Point (II)	North Channel (III)	Mid Channel (IV)	South Channel (V)	Bowerman (VI)	North Bay (VII)	South Bay (VIII)	Entrance (IX)	Entire Estuary
Marsh Phanerogams1/	0.10 (24)	0.24 (17)	0.45 (12)	0.19 (0)	0.48 (6)	1.90 (6)	9.40 (10)	3.20 (7)	0 (0)	16.0
Zostera spp.2/	0 (0)	0.32 (23)	1.70 (46)	29.00 (78)	3.80 (50)	14.20 (49)	41.90 (46)	33.30 (73)	1.58 (25)	125.8
Benthic Algae3/	0.12 (29)	0.58 (41)	0.38 (10)	8.1 (22)	2.8 (37)	12.70 (44)	37.40 (41)	8.50 (19)	0.70 (11)	71.3
Phytoplankton	0.19 (46)	0.24 (17)	1.16 (31)	0 (0)	0.48 (6)	0.27 (1)	2.10 (2)	0.54 (1)	3.96 (63)	8.9
Total for Plant Sources in Estuary	0.41	1.38	3.69	37.29	7.56	29.07	90.80	45.54	6.24	220.0 (19)
Rivers4/										893.1 (75)
Pulp and Paper Industry Effluents5/										83.0 (7)
Total All Sources										1198.1 (100)

1/Marsh plants = total for each predominant type in each region.
2/*Zostera* productivity based on maximum value from Phillips, 1972 = 1,460 $gC/m^2/yr$.
3/Based on mean of all algal values weighted by cover in estuary = 650.95 $gC/m^2/yr$.
4/Total from table 12.
5/Converted from unpublished Seattle District BOD data to organic carbon using relationship in Helms (1970).

with broad tidal flats (i.e. mid-channel, Bowerman, North Bay, South Bay). Sediment-associated microalgal production in these areas is also high. Macroalgal production is greatest in areas where hard substrata (e.g., cobble, roots) exists in the intertidal zone (i.e., the shoreline along the south channel).

Temporal variations in organic carbon input by the various sources also occur (figure 13). Changes with time are based on data presented in several studies. The studies included: Stockner, et al. (1979) and Stockner and Cliff (1979) for phytoplankton; Sand-Jensen (1975), Beyer (1979), and M. Kentula (personal communication, Oregon State University) for Zostera; Pamatmat (1968) and the present study for benthic algae; and the present study for phanerogams. River input variations are from flow data presented in Duxbury, 1979, and carbon data in Naiman and Sibert (1978).

Allochthonous material and eelgrass contribute most of the carbon to the system during winter months (figure 13). In spring and summer, algae (benthic and planktonic) are the most important carbon sources. An autumn die off of vascular plants results in the primary input of particulate organic material to the estuary from that source during early winter. Nixon and Oviatt (1973) reported that phytoplankton contributed approximately 50 percent of total production during winter to a salt marsh embayment in New England. They also found that sediment microflora contributed about 40 percent and macrophytes contributed about 10 percent during this period; sediment associated algal production remained between 30 and 40 percent throughout the year; and the contribution of macrophytes peaked (55 percent) in fall when phytoplankton production declined to 10 percent.

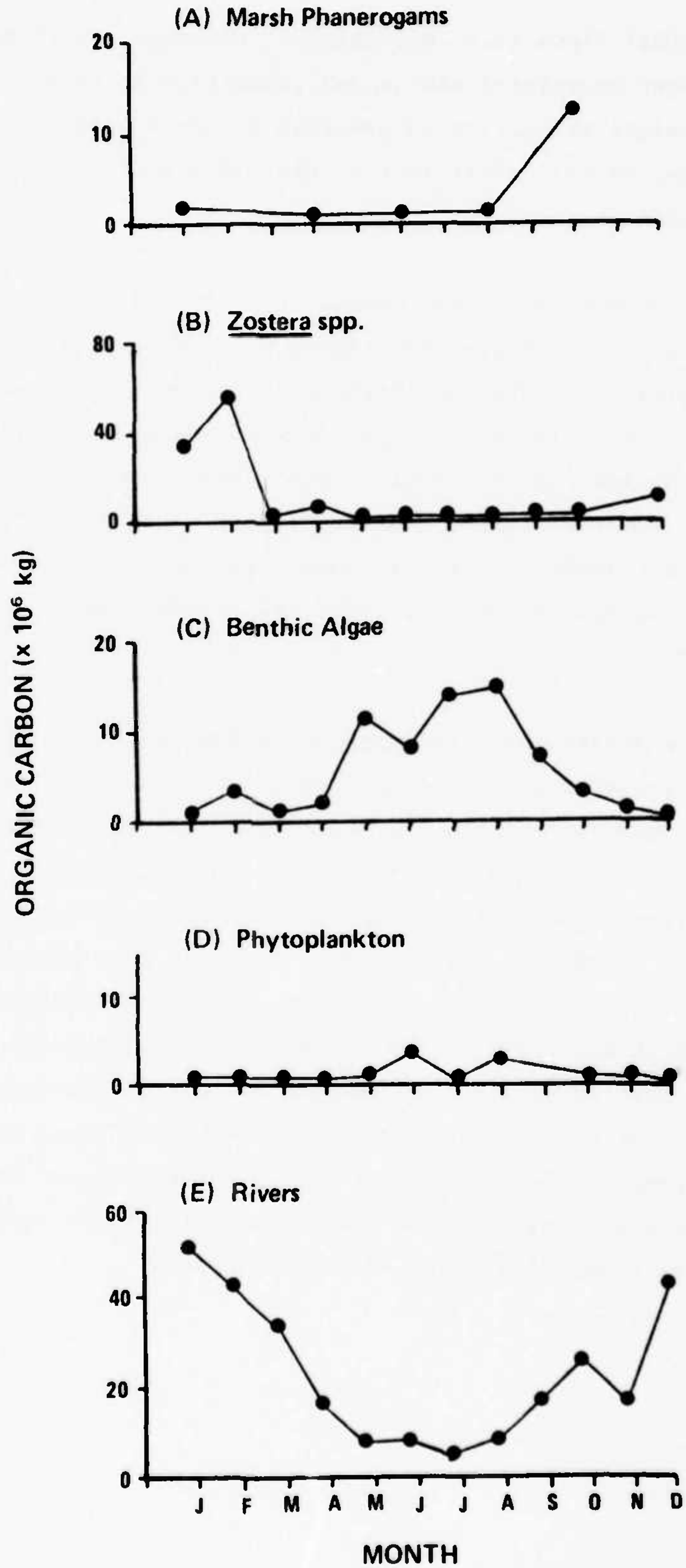

Figure 13. Temporal Changes in Organic Carbon Input to the Estuary by Each Source

IMPACTS OF THE WIDENING AND DEEPENING PROJECT ON PRIMARY PRODUCTION AND ORGANIC CARBON SOURCES

Existing and proposed navigation channel dimensions are shown in figure 14. Widening and deepening the channel could affect sources of organic carbon by altering several environmental conditions. These conditions include turbidity, siltation rate and location, salinity, water temperature, toxicant distributions, nutrient distributions, and hydrodynamics. In addition, benthic plants could either be removed or buried by dredging and disposal activities. The impact of each of these disturbances on the sources of carbon will be addressed in the following sections.

Quantification of the impact is hampered by a lack of quantitative data on cause and effect relationships between disturbances and the sources of carbon. The approach taken here is to evaluate impacts using a simple model in conjunction with the best available (quantitative or qualitative) estimates of the expected degree to which a carbon source is disturbed. Due to a paucity of information on the relative importance of various sources of carbon to the estuary (see Introduction) the impacts relative to secondary production (i.e., animal) are not evaluated.

The model which considers impacts on primary producers is:

$$Y = \sum_{S=1}^{N} P_S A_S T_S$$

where, Y = net annual carbon contribution from all primary producers,

S = the categories of primary producers,

P = net daily productivity rate for each primary producer category,

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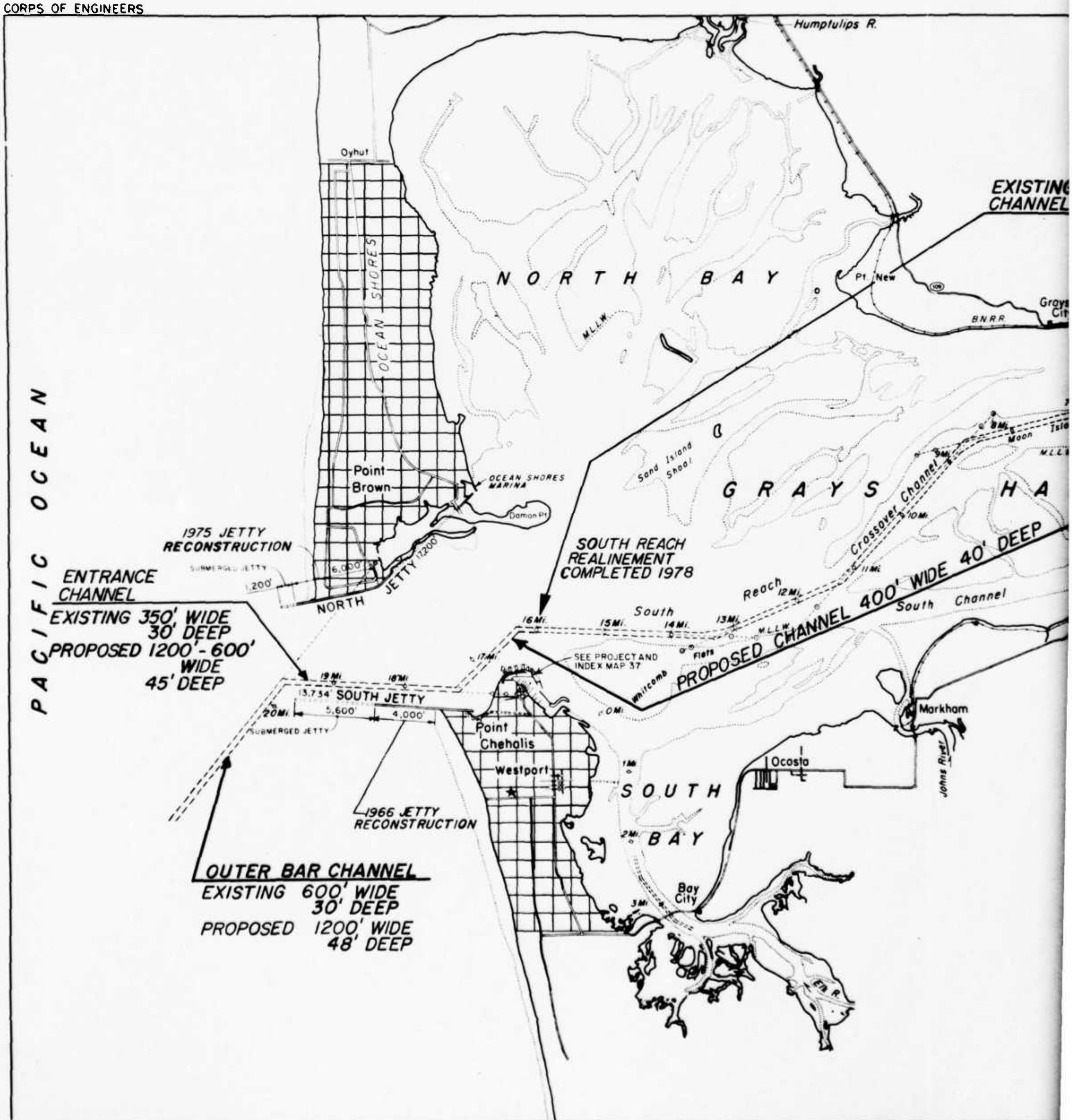


Figure 14.

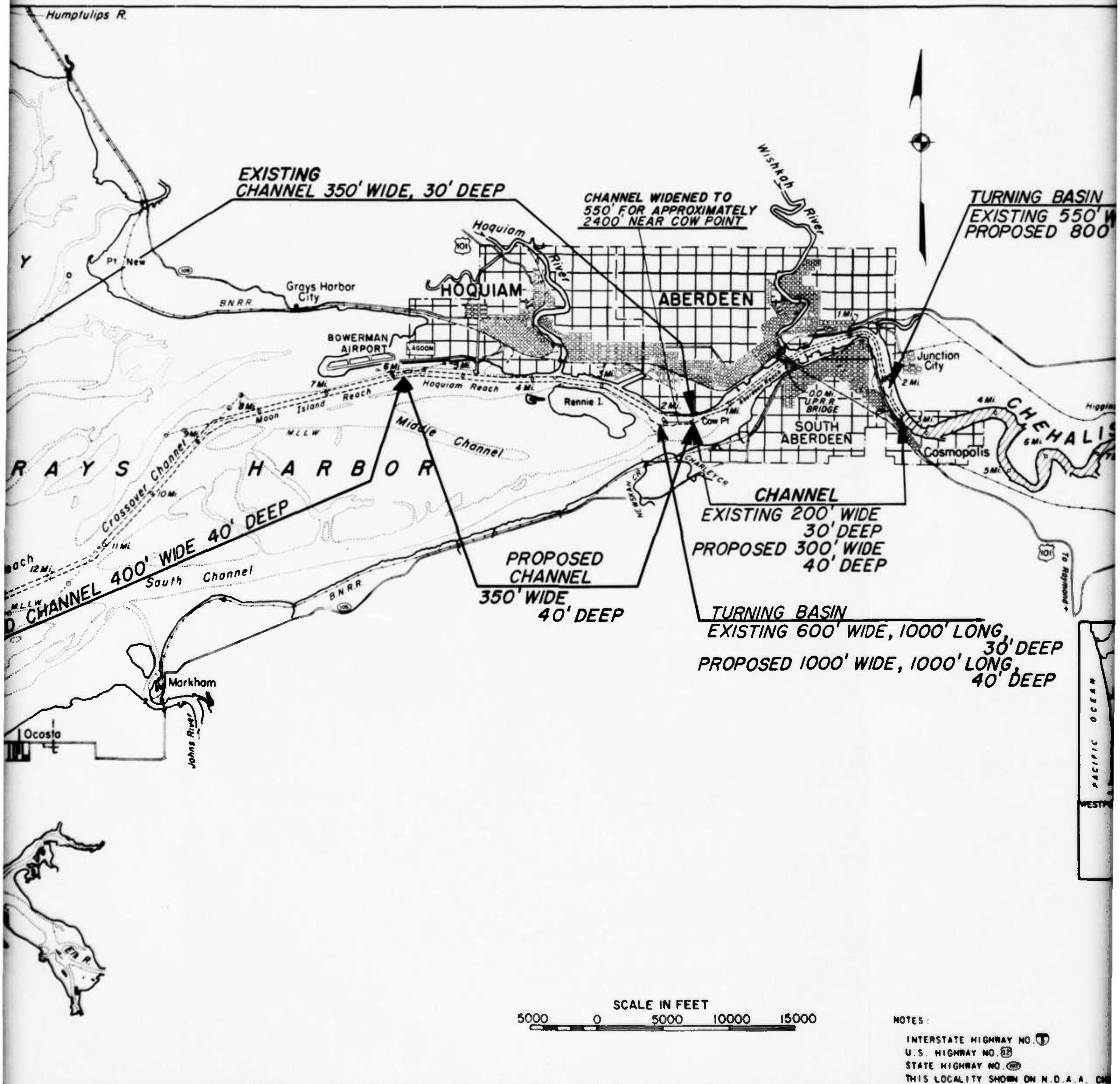
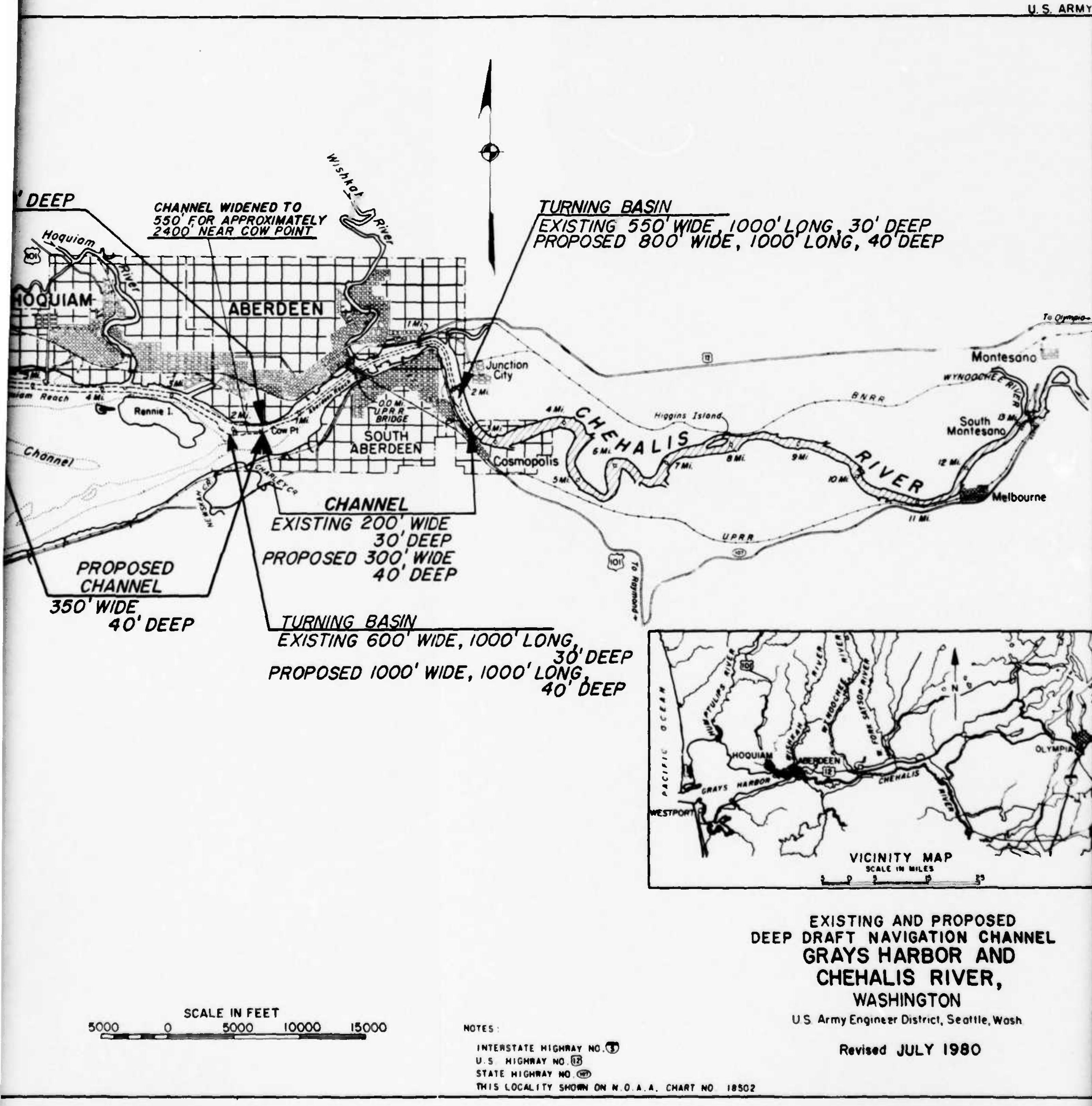


Figure 14. Existing and Proposed Navigation Channel Dimensions in Grays Harbor Estuary



...nd Proposed Navigation Channel
... Grays Harbor Estuary

A = the areal coverage of each of these categories, and

T = the duration (in days) that members of each primary producer category is fixing carbon.

Turbidity and Siltation. Two sites within the estuary may receive some dredged material. These sites are located in deep water (approximately 70 feet (25m)) between Westport and Damon Point (referred to as the Point Chehalis disposal site) and in a deep (approximately 60 feet (22m)) hole near the South Jetty. A study of currents using seabed drifters released at these two sites, in the open ocean near the mouth of the estuary and at other sites within the estuary, was conducted in 1980 and 1981 by the Seattle District, Corps of Engineers. The majority of the drifters released at the Point Chehalis site were recovered at Damon Point and in North Bay. No drifters released at the South Jetty site were recovered in the estuary. These results suggest that some material disposed of in the vicinity of the Point Chehalis site at certain times of the year or under certain conditions will eventually return to the estuary and navigation channel. Associated with this sediment recycling will be increased turbidity and sedimentation in the Damon Point and North Bay areas where dense beds of eelgrass and benthic algae exist. (Many drifters were recovered near Sand and Goose Islands, indicating possible areas of accretion). In a worst case situation where most of the dredged material (ca. 22 million c.y.) is disposed of at the Point Chehalis site, a measurable increase in turbidity and siltation of these areas may occur. Dredging of the channel may take up to 3 years, and the assumption can be made that primary productivity in a certain area in the Damon Point-North Bay region may be reduced significantly. For calculating impacts of turbidity and siltation in this worst case situation using the model, I will assume that 2 percent of Region IX and 5 percent of Region VII benthic primary productivity would be eliminated for a period of greater than 1 year. Recolonization by benthic plants of newly deposited material may occur after the initial dredging and disposal activities cease.

Phytoplankton productivity probably will be impacted primarily in the immediate region of the disposal site and over shallow mudflat areas in the plume of the disposed material during high tides. I will assume that phytoplankton productivity in 1 percent and 2 percent of the area in regions IX and VII will be eliminated for greater than 1 year by this worst case situation. Because marsh phanerogams are not located in the predicted plume area, no change in the productivity of this source is expected.

Turbidity is increased in the waters near an operating dredge. In Grays Harbor, water quality monitoring associated with maintenance dredging operations indicate that substantially increased turbidity is limited to a radius of about 150 feet around the dredge. This area is very small compared to the total area in the estuary occupied by primary producers. It is assumed, for the purposes of impact analysis, that there will be no appreciable change in primary production caused by working dredges.

Changes in shoaling patterns caused by modified channel dimensions could affect the distribution of benthic plants. Studies by Seattle District of shoaling indicate that project caused changes will be undetectable in the main channel. Modifications in turning basin morphology will tend to increase the rate of shoaling in those areas. However, essentially no benthic primary production occurs in turning basins. Therefore, it was assumed that any changes in sedimentation patterns and rates will have no effect on primary productivity.

Other Water Characteristics. The metabolic rate of aquatic plants is partially controlled by temperature and salinity. Conceivably, any changes in water temperature and salinity could result in changes in primary production in the estuary. Loehr and Collias (1981) evaluated the impact of the widening and deepening project on water characteristics in Grays Harbor. They concluded that the project would not significantly alter water characteristics (i.e., dissolved oxygen,

temperature, salinity) in the estuary. They did indicate that offshore upwelled water during summer may intrude into the estuary to a greater degree than at present. This will result in a slight cooling of the outflowing surface waters in the outer estuary. These upwelled waters are generally rich in inorganic nutrients which could enhance productivity in this region. Their analysis is not detailed enough to draw any conclusions other than slight changes in productivity (primarily in phytoplankton) may occur. It is assumed that the degree of change will be minimal and that any changes are restricted to the outer estuary regions.

Tidal Fluctuations. The project will slightly increase the volume of water in the estuary. Because of this, the rate of movement of water in and out of the estuary will be affected. Emergence (and submergence) time partially controls the distribution of intertidal benthic plants, and changes in this parameter could affect productivity. Studies of changes in emergence time caused by the project were conducted by Seattle District. These changes were estimated to be on the order of less than 1 minute. From this information, I conclude that primary productivity will not be affected by changes in the emergence time caused by the project.

Toxicants. Plants utilize dissolved materials from the water column and the sediments for their growth and are an integral part in mineral cycling in estuarine ecosystems (Gunnison, 1978). Some toxicants present in estuaries have been shown to be taken up by plants (e.g., Gallagher and Kibby, 1980; Ragsdale and Thorhang, 1980), incorporated into their tissues, and detrimentally affect plant growth. Further, these toxicants can be passed to consumers through herbivory and the detrital based food web.

Seattle District has determined through field studies that some contaminants are present in Grays Harbor sediments. These include trace metals and organic compounds. Although assays of the effects of some of

these toxicants on plant uptake and metabolism have been conducted, it is difficult to extrapolate these in vitro results to field conditions. I assume that the mode of impact will be through the resuspension of sediments containing toxicants. The plume of toxicants presumably would generally follow sediment dispersal patterns. A worst case condition would exist with disposal of dredged material containing contaminants within the estuary. Disposal at Point Chehalis would result in a redistribution of toxicants over mudflats containing benthic algae and eelgrass. Considerable dilution of toxicants will occur shortly after disposal, and I assume that the effect of toxicants on the growth, survival, and productivity of aquatic vegetation will be negligible. There may be, however, a slight increase in the concentration of certain toxicants in plant tissues in the Point Damon-North Bay areas, and these toxicants may reach higher levels of the food web. Bioaccumulation tests to be conducted by Seattle District will examine this.

Removal and Burial. Approximately 16 km^2 of intertidal areas in Grays Harbor have been used for dredged material disposal since 1940 (Smith, et al., 1976). This has resulted in either permanent or temporary elimination of aquatic vegetation, and a decline in the total amount of carbon reacing the aquatic ecosystem. At the present time, some vegetated wetlands are located in a proposed disposal site near Junction City. These wetlands do drain via small streams into the Chehalis River near Cosmopolis. The impact of the loss of this vegetation on the carbon budget of the entire estuarine system is probably undetectable. Impacts to the local (i.e., within the Junction City disposal area) bogs and swamps may be significant, however.

Channel modifications will result in the removal of approximately 1 acre and 8 acres (total = 3 hectares) of intertidal land in the Cow Point and South Aberdeen areas, respectively (figure 14). Losses in terms of primary productivity based on the productivities of the types of vegetation found in these two areas are 3.2×10^3 KgC/yr for the Cow Point area (primarily algal vegetation) and 22.8×10^3 KgC/yr (half

salt marsh and half algal vegetation). This represents a decline of approximately 1.5 percent (= 26.0 x 10^3 KgC/yr) of carbon fixation from the total for these two regions (i.e., regions I and II).

Changes in estuarine primary production caused by widening and deepening the navigation channel and associated proposed disposal alternatives are summarized in table 14. Values in the table are based on estimates of changes discussed above and on the incorporation of these estimates into calculations using the mathematical model presented above. Disposal at the Point Chehalis site and removal of intertidal areas will cause the largest changes in annual primary productivity. If disposal is carried out in the ocean and intertidal areas are avoided by modifying proposed channel dimensions and alinements in narrow reaches, much of this impact will be avoided. No impact of the project on fluvial sources of carbon is expected, although changes in flow rates of the Chehalis River may result in changes in the locations of deposition of particulate organic carbon in the estuary.

TABLE 14

CHANGES IN ANNUAL PRIMARY PRODUCTIVITY
CAUSED BY THE WIDENING AND DEEPENING PROJECT
(Values are in 10^3 KgC/yr; percentage change is in parentheses)

	Disturbance							
Source	Turbidity and Siltation From Disposal at Pt. Chehalis	Turbidity Associated With Dredging	Shoaling	Hydrodynamics	Emergence Time	Toxics	Burial and Removal	Total
Marsh Phanerogams	0	0	0	0	0	0	-11 (1)3/	-11 (1)
Zostera spp.	-2127 (2)1/	0	0	0	0	0	0	-2127 (2)
Benthic Algae	-1884 (3)1/	0	0	0	0	0	-58 (1)3/	-1942 (3)
Phytoplankton	-82 (1)1/	0	0	0	0	0	0	-82 (1)
Total	-4093 (2)2/	0	0	0	0	0	-69 (1)3/	-4093 (2)2/

1/Changes in values for regions VII and IX.

2/Based on total of all plant sources in the estuary.

3/Changes in values for regions I and II.

CONCLUSIONS

Primary productivity measurements for Grays Harbor estuary are few. The area contains extensive mudflats with eelgrass and benthic algae beds and these plants probably contribute most of the carbon to the estuary relative to estuarine phytoplankton and marshes. The primary source of carbon is allochthonous. The major mode of transport of this material is the Chehalis River.

Increased turbidity and siltation from the discharge of dredged material in open water areas near Point Chehalis may reduce productivity in nearby algae-eelgrass beds. Chemical contaminants in disposed material may increase concentrations of these contaminants in plant tissue. Removal of intertidal areas in the inner harbor during the proposed project will also result in a permanent loss of some organic material input. The disposal of dredged material on wetland vegetation near Junction City will cause a permanent loss of carbon input to the aquatic ecosystem. This latter loss would have its primary impact in the Junction City area.

Calculations using a simple mathematical model show that approximately 2 percent of estuarine primary production (0.34 percent of the total organic carbon input from all sources) could be lost due to the project. This reduction would be caused primarily by turbidity and siltation related to the redistribution by currents of dredged material disposed of near Point Chehalis. Removal of intertidal areas would also impact productivity in some areas of the inner harbor. Disposal outside of the estuary and modifications of the navigation channel to avoid intertidal areas would reduce or eliminate these impacts.

RECOMMENDATIONS

Impacts of navigation channel modifications on the sources of carbon to the estuary appear to be minimal. However, the estimates used in the present analysis regarding rates were largely taken from studies conducted in other west coast estuaries. Variation among sites in productivity rates for a plant species may be large (Turner, 1976; Kibby, et al., 1980), and very few studies exist on Pacific Northwest estuaries to judge the reliability of assuming that rates are the same among these estuaries. Data on phytoplankton and sediment associated microalgal productivities are about 15 years old, and conditions may have changed since that time. New information on productivity rates for all major species in Grays Harbor, an intensive study of productivity in the areas that may be impacted, and an estimate of the degree of impact the area will receive, would refine impact estimates.

Information on organic input from rivers was based on estimates from rivers in other areas. This information may be adequate; however, site specific data are necessary to verify this conclusion. If, for example, river input is overestimated in the present study, the relative impact of the navigation project on the amount of total carbon available is increased. If, however, this input is conservatively estimated, the project impact is decreased.

What does a loss of 2 percent of organic carbon contributed by estuarine plants mean in terms of secondary production? Simenstad and Eggers (1981) indicate that juvenile salmonids feed extensively on benthic invertebrates in the estuary. These invertebrates utilize particulate and dissolved organic carbon for food. A study of secondary production and carbon sinks would allow conclusions to be drawn regarding the impact of a reduction in primary production on secondary (and higher) production.

The uptake of toxicants by plants may effectively redistribute these materials to other areas and higher trophic levels. Bioaccumulation studies using the plant species most likely to be exposed to increased levels of toxicants would aid in interpreting the importance of this impact.

These recommended studies would refine many of the estimates of productivity, carbon input, and impact. Due to the relatively small change in productivity associated with the worst case scenario, the author suggests that further refinement of these estimates is not warranted for assessing the impact of the proposed widening and deepening project. Should the design of the project change in a manner that carbon sources may be further impacted, further analysis of impacts to carbon sources and sinks should be undertaken.

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